

Search for Sterile Neutrinos Using the MiniBooNE Beam

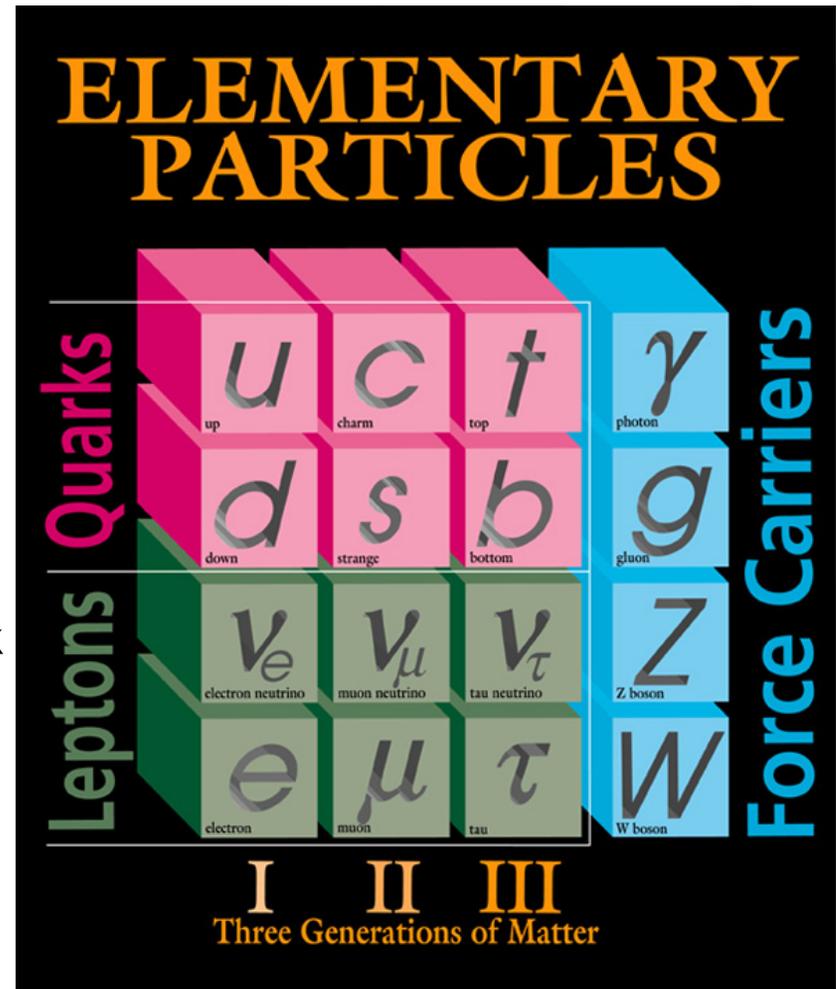
Michel Sorel, Columbia University
Dissertation Sponsor: Prof. Janet Conrad

- Sterile Neutrinos and Neutrino Oscillations
- MiniBooNE Beam and Detector
- $\nu_{\mu} n \rightarrow \mu^{-} p$ Interactions
- Muon Neutrino Disappearance Search

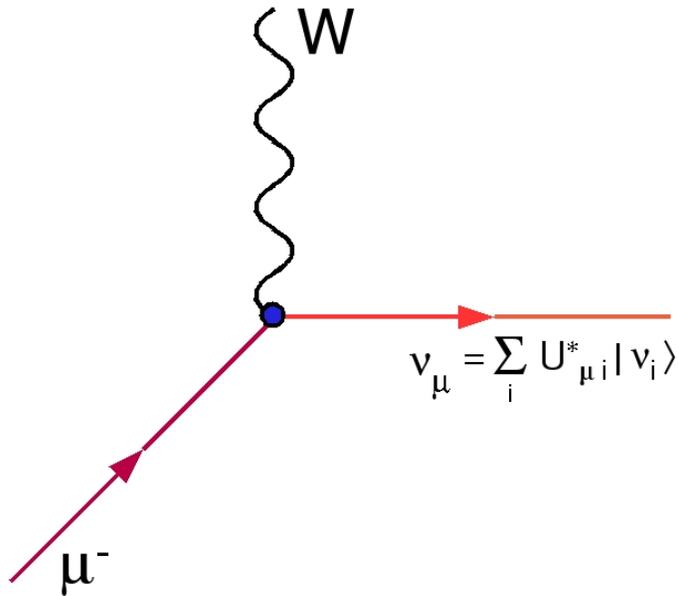
New York
March, 2005

Neutrinos: What We Know

- Lightest known fermions
- No color (no QCD interactions)
- No charge (no EM interactions)
- Only weak interactions
- Three light “active” neutrino families
- Paired with charged leptons in weak isodoublets
- Non-zero masses and mixings



Neutrino Mixing



Flavor eigenstates $|\nu_{\alpha}\rangle$ ($\alpha = e, \mu, \tau$):

- Identified with charged lepton:
Produced in decay with lepton \mathbf{l}_{α}^{+}
Produces lepton \mathbf{l}_{α}^{-} in CC interaction

Mass eigenstates $|\nu_i\rangle$:

- Determines free particle evolution
Solutions to Schrödinger's Equation
 $|\nu_i(\mathbf{x})\rangle = e^{-i\mathbf{p}\cdot\mathbf{x}}|\nu_i(\mathbf{0})\rangle$

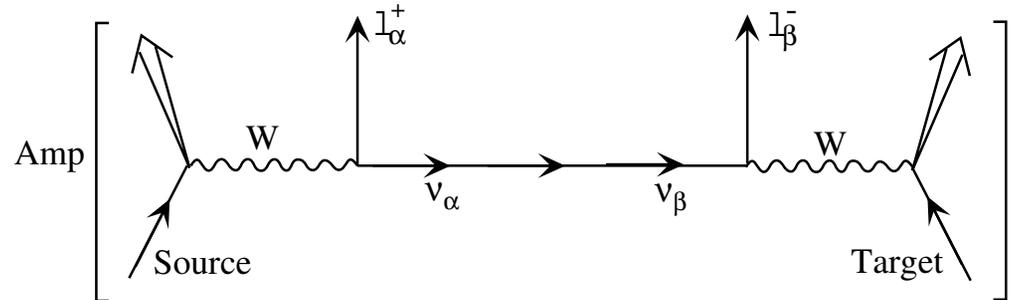
Flavor/mass eigenstates related by unitary MNS mixing matrix U :

$$|\nu_{\alpha}\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

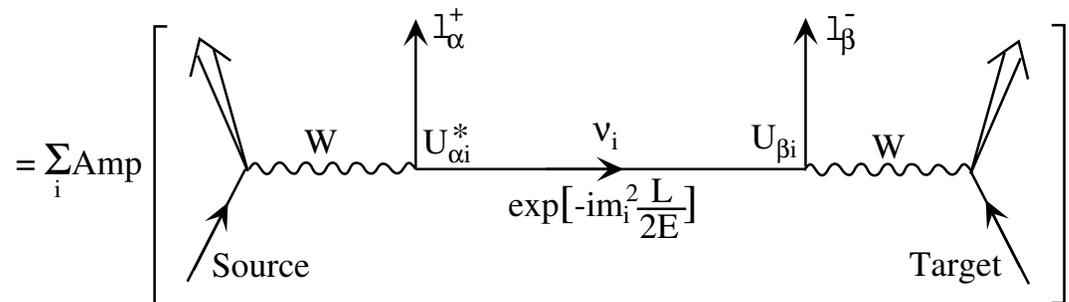
Mass splittings and mixings determined experimentally via neutrino oscillations

Neutrino Oscillations

- **Appearance:** start with flavor α and observe different flavor β after some time/distance



- **Disappearance:** start with known amount of ν_α , find less ν_α later

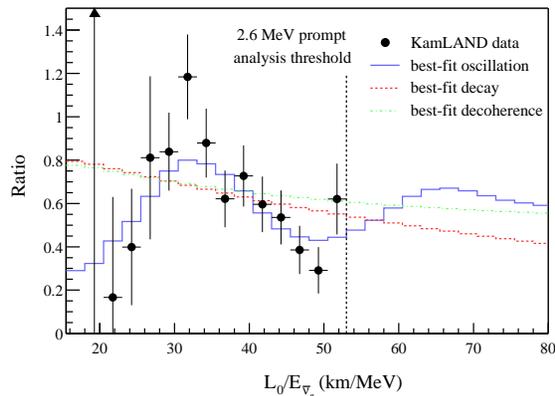


- Oscillation probability:

$$\mathbf{P}(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(\mathbf{U}_{\alpha i}^* \mathbf{U}_{\beta i} \mathbf{U}_{\alpha j} \mathbf{U}_{\beta j}^*) \sin^2[1.27 \Delta m_{ij}^2 (\mathbf{L}/\mathbf{E})] + 2 \sum_{i>j} \Im(\mathbf{U}_{\alpha i}^* \mathbf{U}_{\beta i} \mathbf{U}_{\alpha j} \mathbf{U}_{\beta j}^*) \sin[2.54 \Delta m_{ij}^2 (\mathbf{L}/\mathbf{E})]$$

- $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
- Non-zero and non-degenerate masses, $U \neq 1 \Rightarrow$ neutrino oscillations

Experimental Evidence for Neutrino Oscillations

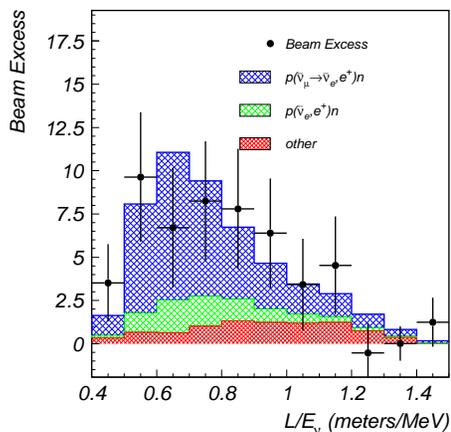
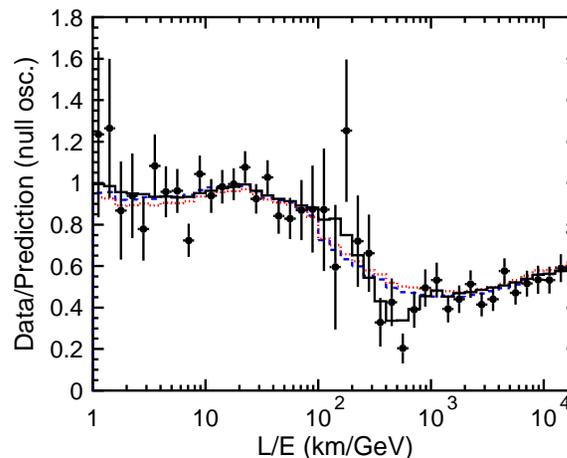


Solar Neutrino Oscillations

- Deficit of ν_e observed from Sun
Cl (Homestake), H₂O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\bar{\nu}_e$)

Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of ν_μ :
Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS will be definitive

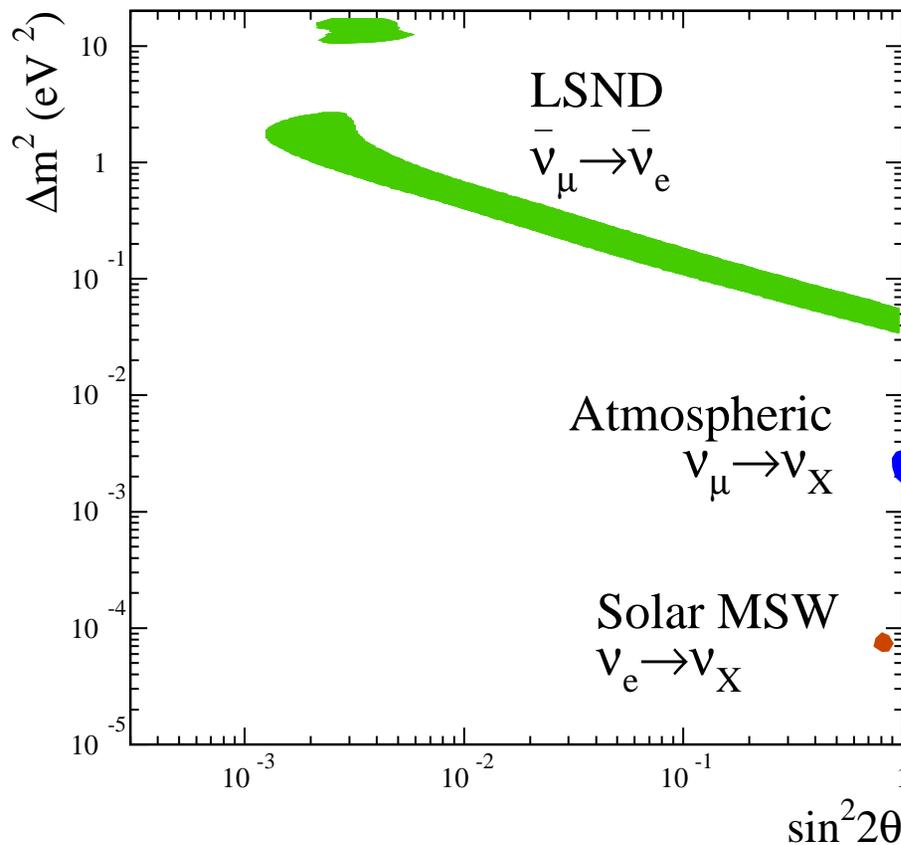


LSND Neutrino Oscillations

- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam produced from μ^+ decay-at-rest
- Unconfirmed by other experiments, but not excluded

Two-flavor Oscillation Parameters

- All individual experimental evidences can be described by a single mass splitting Δm^2 and a single mixing parameter $\sin^2 2\theta$:

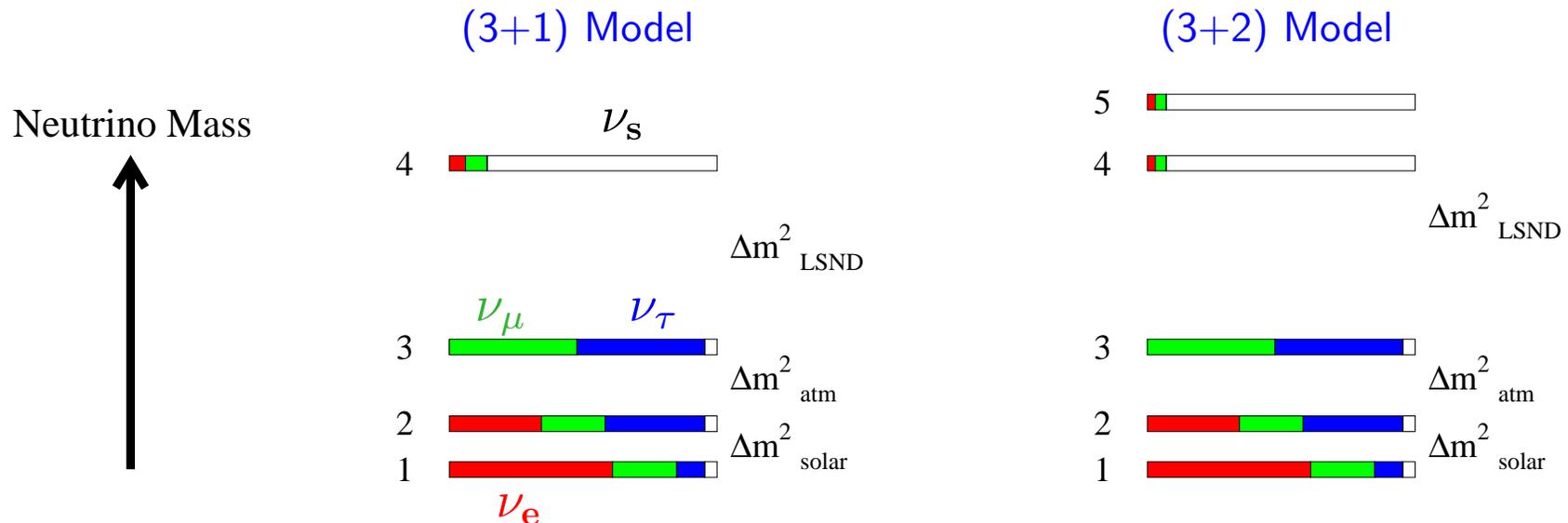


- $\mathbf{P}(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2[1.27\Delta m^2(\mathbf{L}/\mathbf{E})]$
- $\mathbf{P}(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2[1.27\Delta m^2(\mathbf{L}/\mathbf{E})]$
- LSND:**
 $\Delta m^2 \approx 0.1 - 10 \text{ eV}^2$, small mixing
- Atmospheric:**
 $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta \approx 1.0$
- Solar:**
 $\Delta m^2 \approx 7 \times 10^{-5} \text{ eV}^2$, $\sin^2 2\theta \approx 0.8$

- Three distinct neutrino oscillation signals, with: $\Delta m^2_{\text{LSND}} \gg \Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}}$

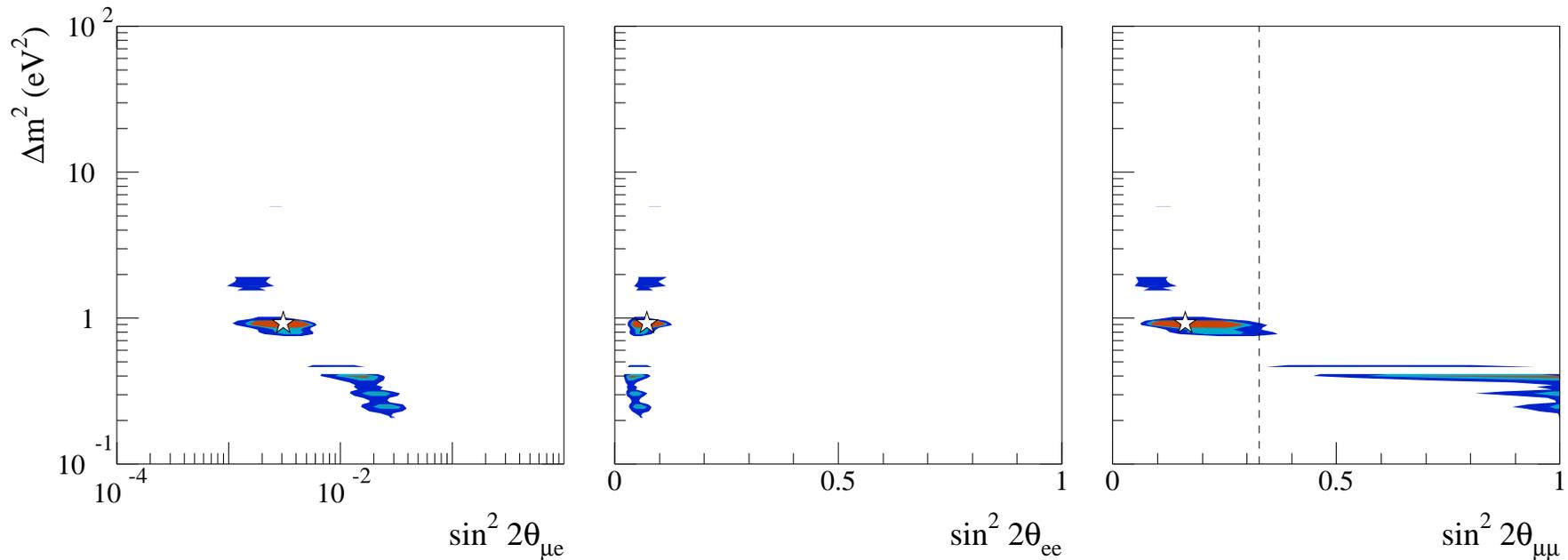
Sterile Neutrinos

- Sterile neutrinos: neutrinos with no weak couplings. In standard electroweak theory, sterile neutrinos are right-handed particles.
- Sterile neutrinos are required by the see-saw mechanism generating neutrino masses
- Neutrino oscillations among active flavors only cannot explain three independent Δm^2 , because only three light, active neutrino species are known to exist from $e^+e^- \rightarrow Z^0$ measurements at LEP
- Active-active plus active-sterile neutrino oscillations allow for three (or more) independent Δm^2 , accommodating solar, atmospheric, and LSND oscillations



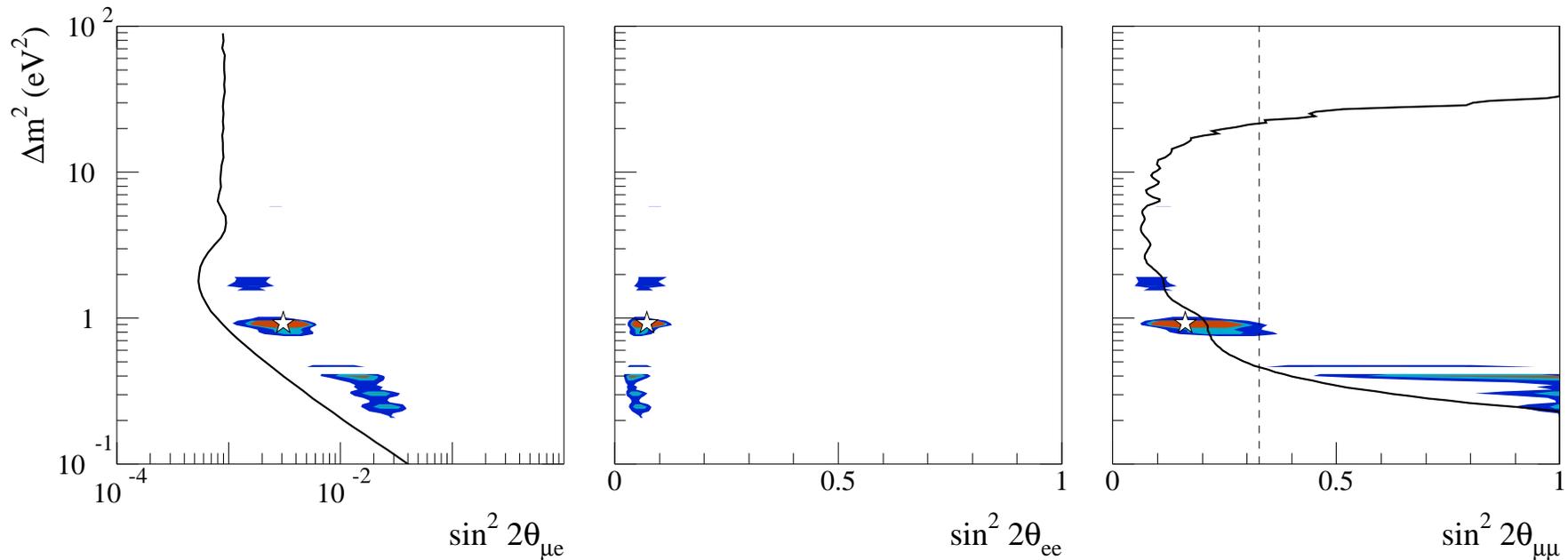
Expectations for Active-Sterile Neutrino Oscillations

- Combined analysis of $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\mu$ oscillation searches, assuming a (3+1) sterile neutrino model, point to following neutrino masses and mixings (MS, J. Conrad, M. Shaevitz, PRD **70**:073004):



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- Solid lines show MiniBooNE sensitivity to $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$ oscillations \Rightarrow “guaranteed” discovery, if LSND due to active-sterile neutrino oscillations!
- Similarly, mixings that are large enough to be observable at MiniBooNE are expected in the favored (3+2) sterile neutrino models, for $0.2 \lesssim \Delta m^2 \lesssim 50 \text{ eV}^2$

Neutrinos: Open Questions

Issues	Questions	Theorists' Poll*
# of Light Neutrinos	3 active + ? steriles	Three
Majorana vs Dirac	$\nu = \bar{\nu}$, 2 vs 4 states per ν , L viol.	Majorana
Masses	degenerate, normal/inverted	See-saw
Mixings	$\theta_{13}, \theta_{23} \stackrel{?}{=} \pi/4$, U real vs complex, CP Violation , Leptogenesis	???
Exotics	Non-osc., CPT-V, decays, μ -mom, etc.	None

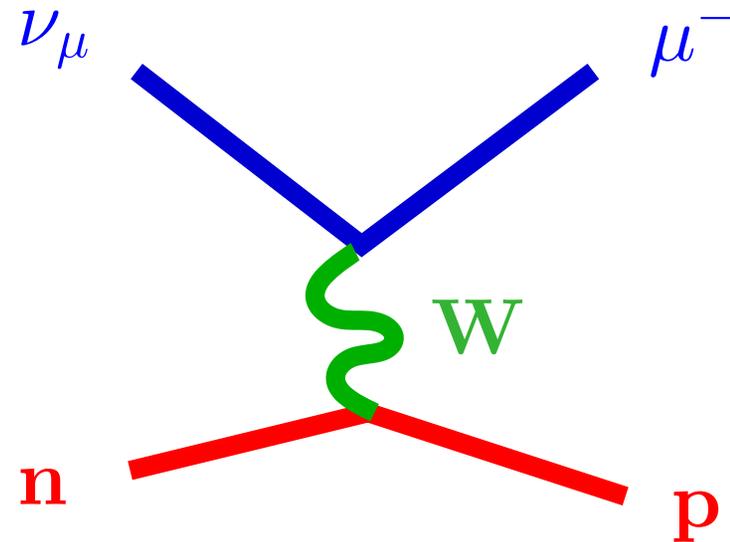
* From S.Parke, FNAL, Nov 2003: *“At least one theoretical prejudice is wrong”*

- **Marked in blue:** studied in the context of sterile neutrino models

Search for Sterile Neutrinos via $\nu_\mu n \rightarrow \mu^- p$ Interactions

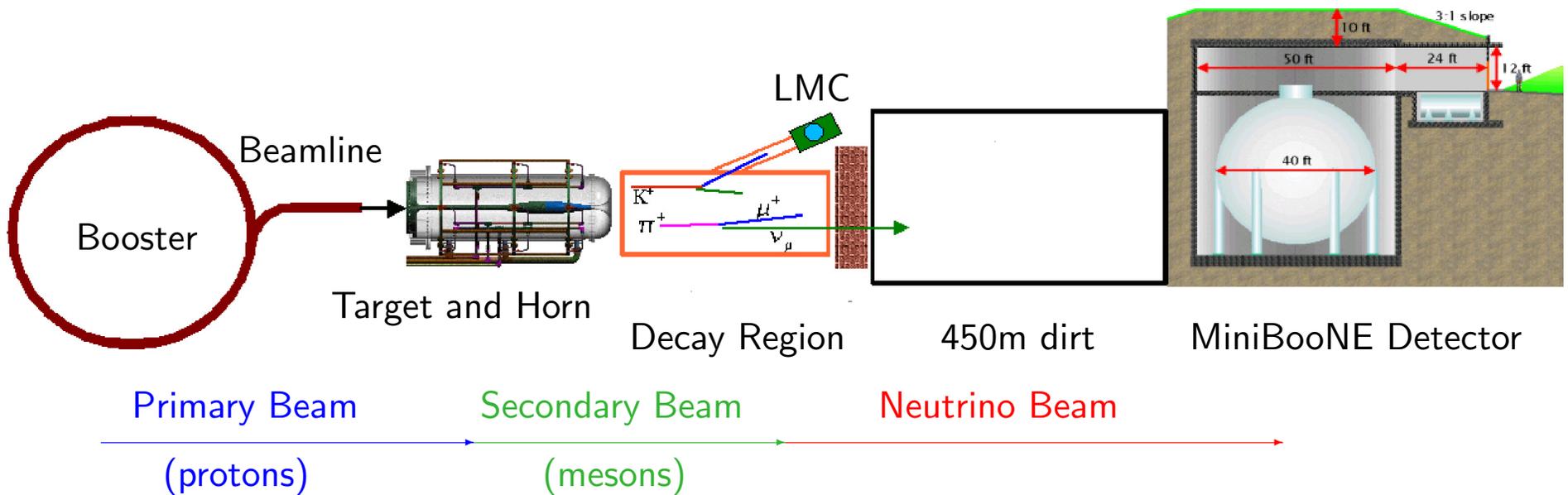
- if $\nu_\mu \rightarrow \nu_s$ oscillations are present between neutrino production and detection, fewer muon neutrino interactions than expected would occur at MiniBooNE
- Oscillation probability depends on neutrino energy, therefore **three** types of muon neutrino disappearance analyses are possible:
 - **normalization-only:** compare overall number of interactions with expectations
 - **shape-only:** look for neutrino energy-dependent distortions in the observed spectrum, compared to expectations (analysis discussed here)
 - **normalization plus shape:** combine both informations

Search for Sterile Neutrinos via $\nu_\mu n \rightarrow \mu^- p$ Interactions (2)



- This analysis uses a sample of **charged-current, quasi-elastic muon neutrino interactions** (CCQE, $\nu_\mu n \rightarrow \mu^- p$) for the disappearance search, because:
 - 2-body kinematics of the reaction allow for the best possible **neutrino energy reconstruction**
 - disappearance analysis in single-detector experiment relies on external neutrino flux and cross-section predictions. The **best-known neutrino process** in the $\simeq 1$ GeV energy range is the CCQE interaction

MiniBooNE Neutrino Beam



Primary Beam: 8 GeV protons from Booster, $8 \cdot 10^{-6}$ duty factor

Secondary Beam: mesons are produced from protons striking Be target, focused by horn, and monitored by “Little Muon Counters” (LMC)

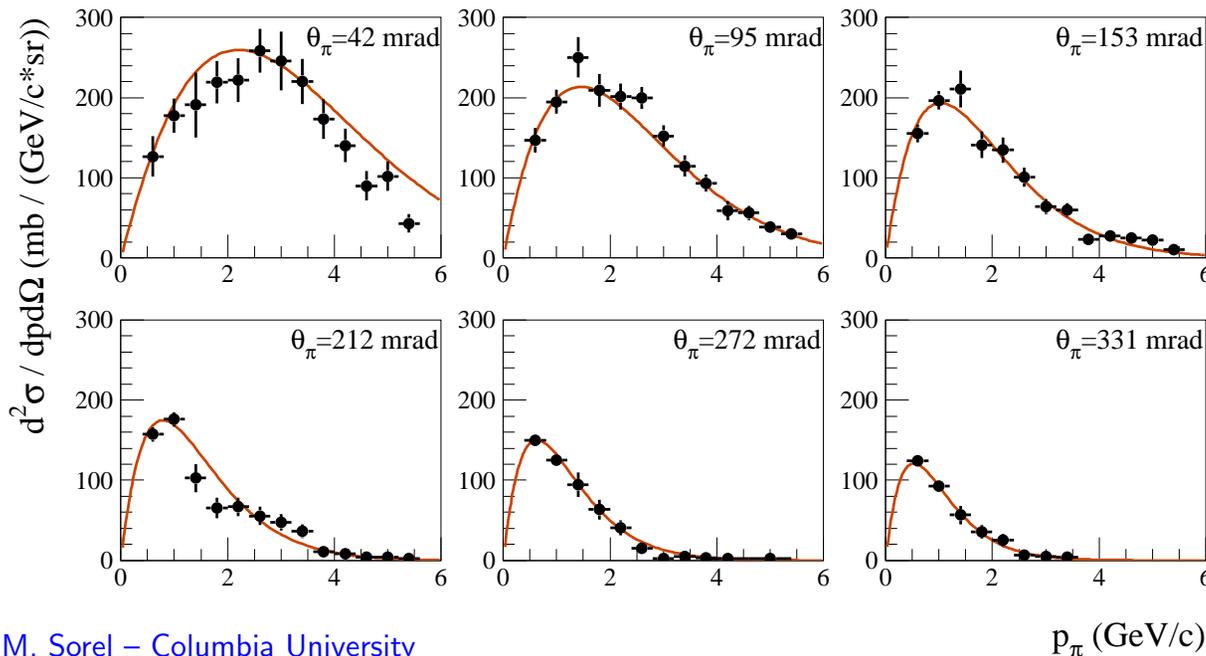
Neutrino Beam: neutrinos from meson decay in 50m pipe, pass through 450m of dirt (and oscillate?) to reach MiniBooNE detector

Neutrino Flux Simulation

- GEANT4 description of the beamline to simulate:
 - primary protons, geometry, materials and magnetic field in target hall and decay region;
 - physics processes governing interactions/focusing/decays of baryons, mesons, and muons.
- Most neutrinos from $\pi^+ \rightarrow \mu^+ \nu_\mu$. Flux uncertainty dominated by uncertainty on $p+\text{Be} \rightarrow \pi^+ + X$, described via Sanford-Wang parametrization:

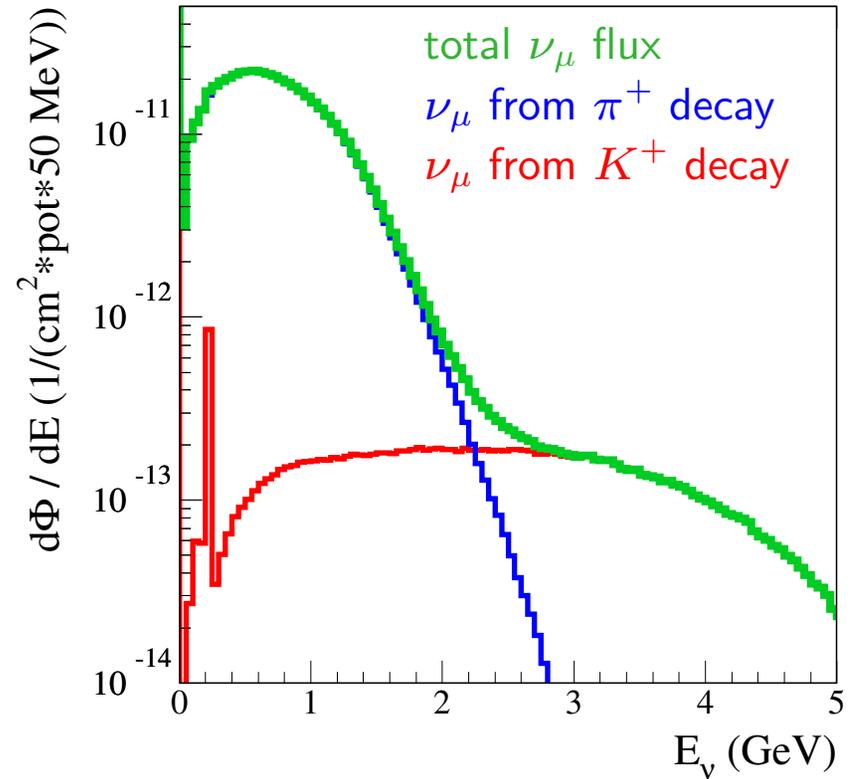
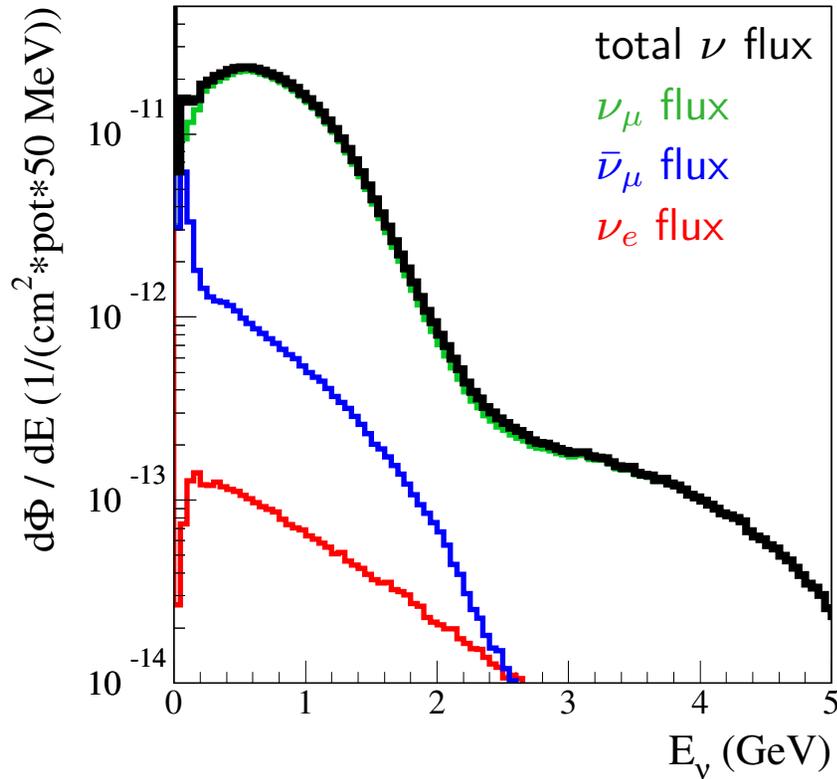
$$\frac{d^2\sigma(p+\text{Be} \rightarrow \pi^+ + X)}{dpd\Omega} = c_1 p^{c_2} \left(1 - \frac{p}{p_{\text{beam}} - c_9}\right) \exp\left[-c_3 \frac{p^{c_4}}{p_{\text{beam}}^{c_5}} - c_6 \vartheta (p - c_7 p_{\text{beam}} \cos^{c_8} \vartheta)\right]$$

- Constrain flux predictions by using existing π/K production data (\Rightarrow BNL E910) as inputs to simulation. Plan to use CERN HARP measurements when available



BNL E910 $p+\text{Be} \rightarrow \pi^+ + X$ data at $p_{\text{beam}}=12.3 \text{ GeV}/c$, compared to Sanford-Wang parametrization in G4

Neutrino Flux Predictions



Neutrino Flavor	Neutrino Parent	Flux ($cm^{-2}pot^{-1}$)	Flux Fract. (%)	$\langle E_\nu \rangle$ (GeV)
all	all	$5.2 \cdot 10^{-10}$	100.0	0.76
ν_μ	all	$4.8 \cdot 10^{-10}$	92.7	0.78
ν_μ	π^+	$4.7 \cdot 10^{-10}$	89.8	0.73
ν_μ	K^+	$1.4 \cdot 10^{-11}$	2.7	2.25
$\bar{\nu}_\mu$	all	$3.5 \cdot 10^{-11}$	6.6	0.49
ν_e	all	$3.1 \cdot 10^{-12}$	0.6	0.94

Neutrino CCQE Cross-Section Predictions

- Neutrino cross-section predictions via NUANCE simulation. Given the MiniBooNE flux, about **40% of all interactions** are expected to be CCQE: $\nu_\mu n \rightarrow \mu^- p$
- Free nucleon CCQE cross-section is described by Llewellyn-Smith formalism:

$$\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_\nu^2} \left[A(Q^2) + B(Q^2) \frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4} \right]$$

$Q^2 \equiv -(p_\nu - p_\mu)^2$, $(s-u) \simeq 4m_N E_\nu - Q^2$, and A, B, C depend on form factors describing the weak hadronic current, parametrized via vector and axial masses

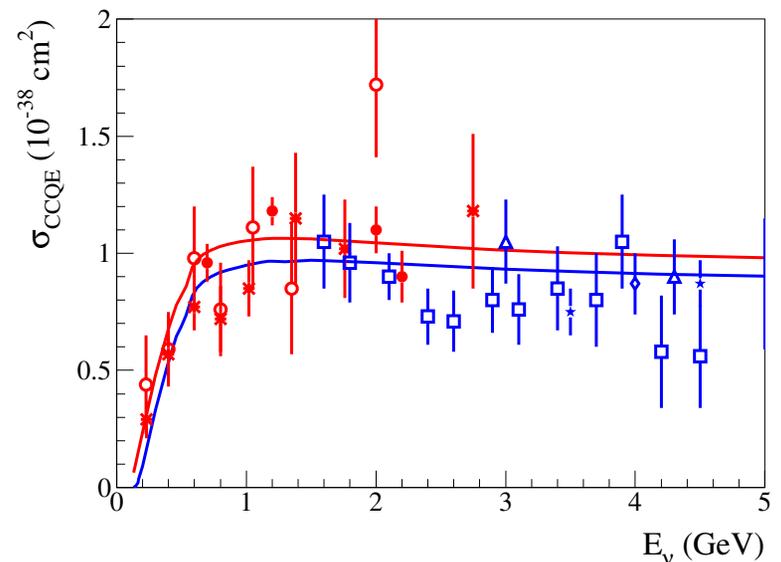
- Target neutrons bound in Carbon nuclei \Rightarrow nuclear effects, in the form of Pauli suppression, Fermi momentum, and final state interactions, are taken into account

Curve: free nucleon NUANCE prediction ($m_A = 1.03$ GeV)

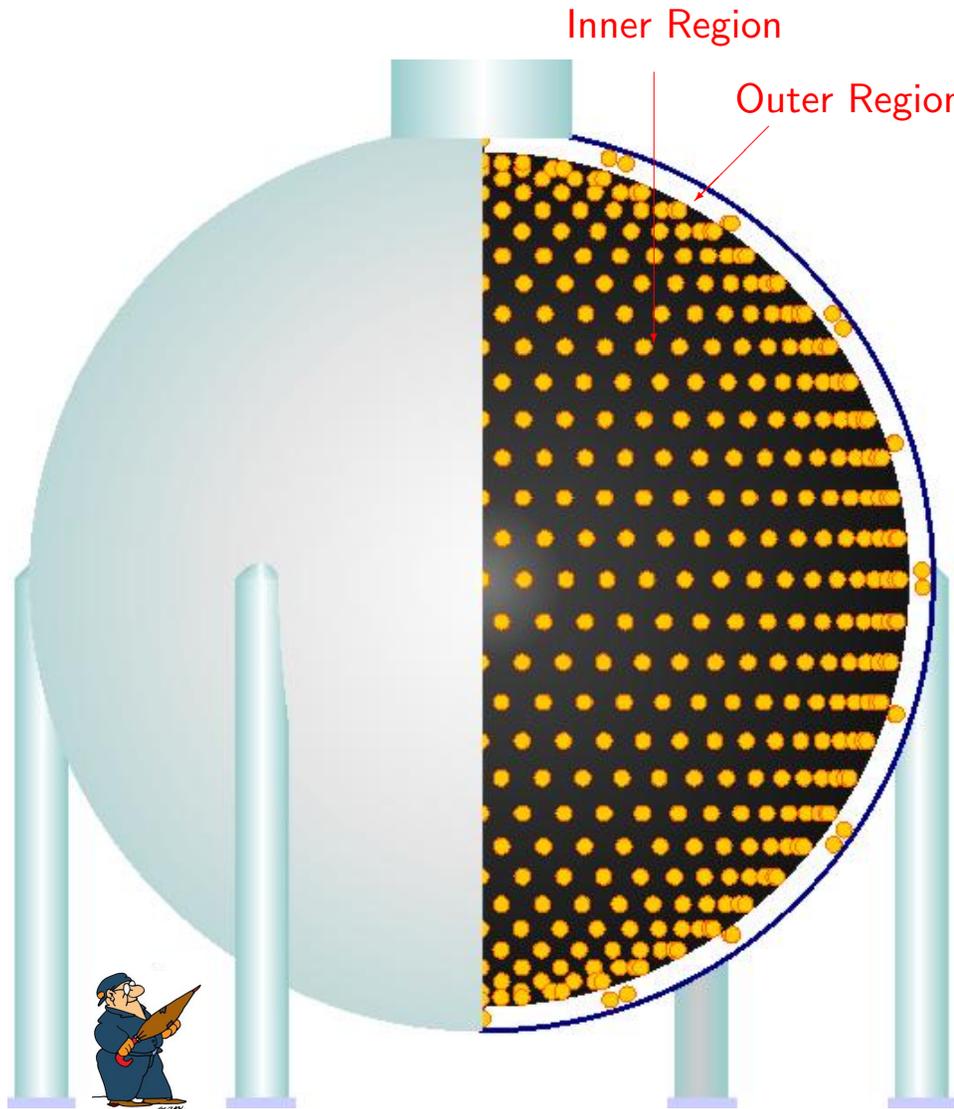
Points: CCQE data on deuterium targets

Curve: bound nucleon NUANCE prediction, with Fermi gas nuclear model ($E_B = 25$ MeV, $p_F = 220$ MeV/c)

Points: CCQE data on heavier targets

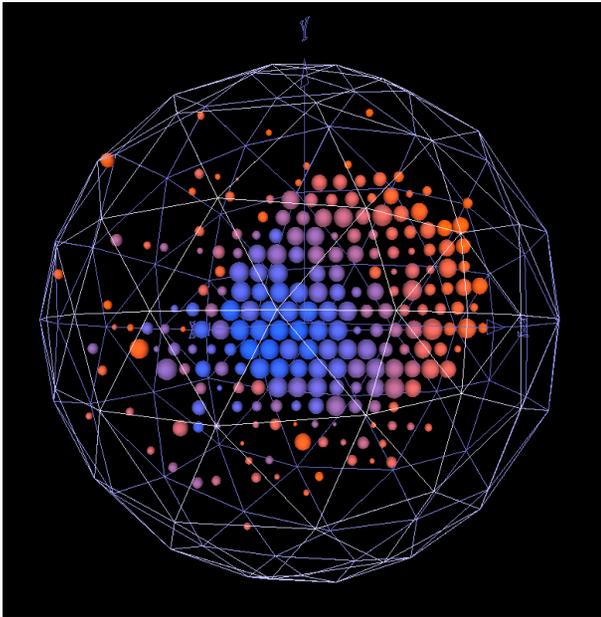


MiniBooNE Detector



- 12m in diameter sphere filled with 800t of undoped mineral oil
- Light tight inner region with 1280 8" PMTs (10% coverage)
- 240 PMTs in outer region (>99% veto efficiency)
- Neutrino interactions in oil produce:
 - Prompt, ring-distributed Cherenkov light
 - Delayed, isotropic scintillation light
- Light transmission affected by: fluorescence, scattering, absorption

Event Reconstruction and Particle ID



- Measure photoelectrons from optical photons reaching the PMT surface:
 - total charge
 - spatial distribution
 - time distribution

● Event Reconstruction:

- correlated electrons from muon decays
- neutrino interaction vertex
- direction, spatial extent, and energy of Cherenkov tracks (e, μ, π^0)
- separate amounts of Cherenkov and scintillation light;
- for CCQE events, full event kinematics: neutrino energy, Q^2 , etc.

● Particle ID: distinguish $e/\mu/\pi^0$

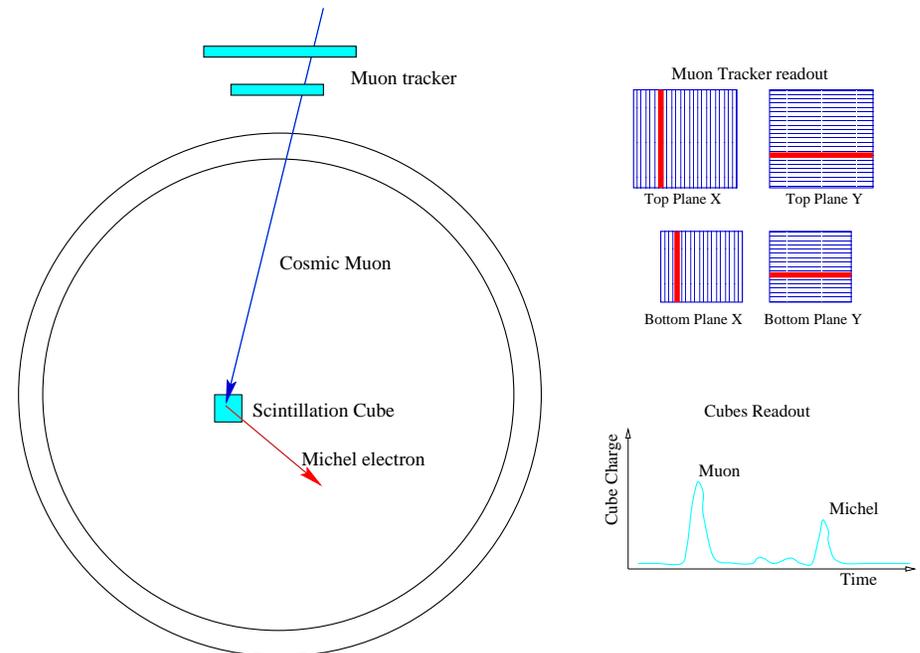
Calibration Samples

Laser Calibration Sample: prompt, isotropic laser light source

- PMT hit reconstruction: PMT time/charge resolution, pre/afterpulsing
- Oil optical properties: absorption, surface reflections, scattering

Muon Calibration Sample:
cosmic rays through tracker, and
stopping in scintillation cubes

- Muons of known direction, decay vertex, pathlength
- Provides independent measurement of muon energy up to 700 MeV



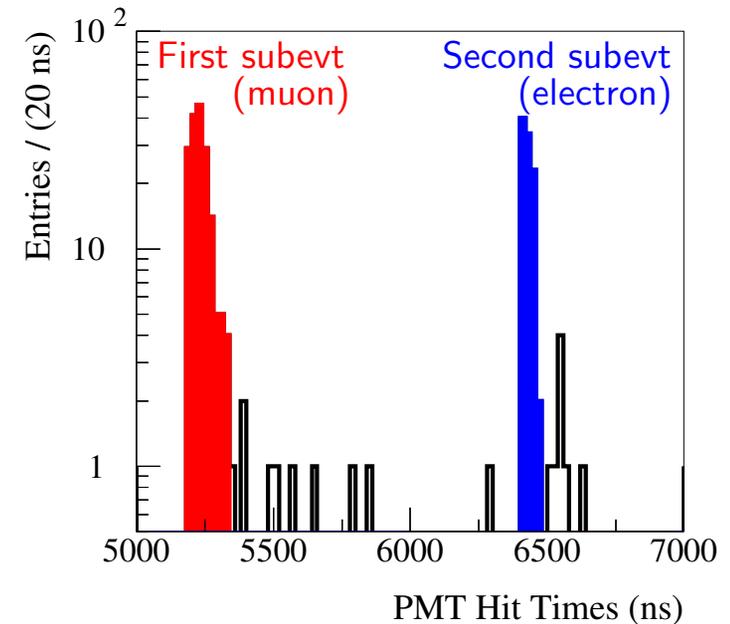
Electron Calibration Sample: Michel electrons from muon decays at rest

- Known energy spectrum between 0 and 52.3 MeV \Rightarrow fix energy scale
- Energy reconstruction accuracy: 14% at 52.3 MeV

CCQE Event Selection Procedure

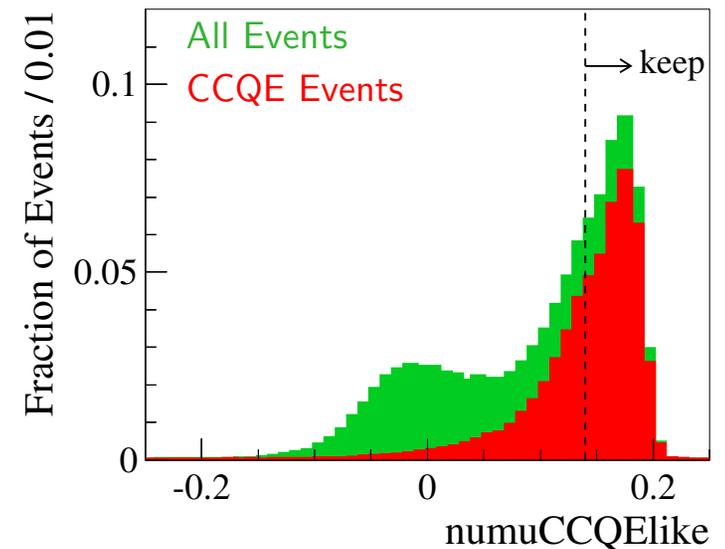
Hit-level and reconstruction-level selection:

- one or two subevents ($\Rightarrow \leq 1$ decay electrons);
- low veto activity, and at least 100 PMT hits in main detector region ($E_{\text{vis}} \gtrsim 50$ MeV);
- mean light emission time within beam spill;
- successful reconstruction, and mean light emission point within fiducial volume ($R < 500$ cm).



Event-level selection:

- Use ten reconstructed quantities as inputs to Fisher discriminant method;
- Quantities related to coarse and fine hit timing structure, and to spatial topology of detected light;
- Algorithm tuned on simulated data to isolate events with a single, muon-like Cherenkov ring, and scintillation light consistent with $\nu_{\mu}n \rightarrow \mu^{-}p$.



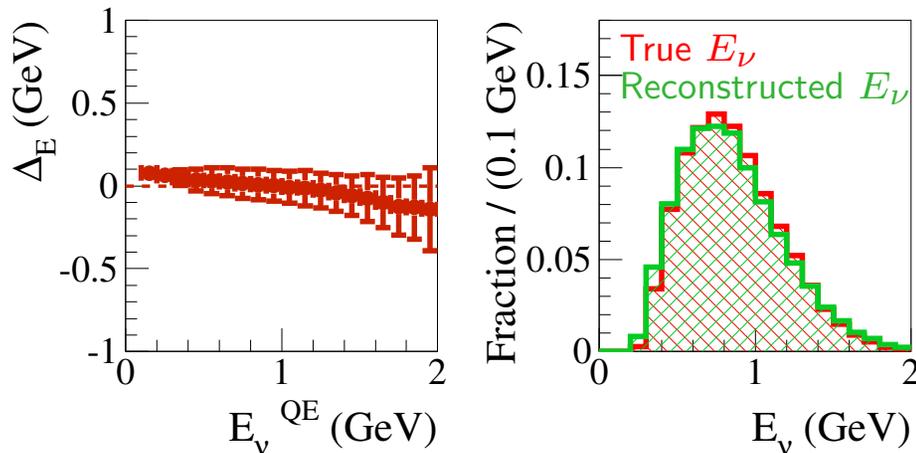
Neutrino Energy Reconstruction

- Obtained from muon energy E_μ and direction θ_μ , via 2-body kinematics:

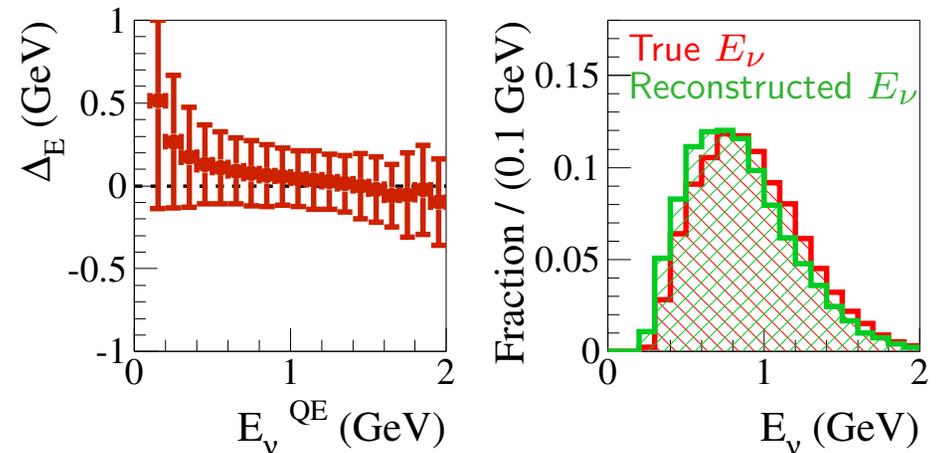
$$E_\nu^{QE} = \frac{1}{2} \frac{2(m_N - E_B)E_\mu + (2m_N E_B - m_\mu^2 + E_B^2)}{(m_N - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu}$$

- Muon and neutrino energy calibrated via simulated data
- $\Delta_E \equiv \text{Mean}[E_\nu^{gen} - E_\nu^{QE}] \pm \text{RMS}[E_\nu^{gen} - E_\nu^{QE}]$ describes biases and resolution

CCQE-only events passing selection



All events passing selection



- Expect 11% (30%) resolution for CCQE-only events (all events) passing selection

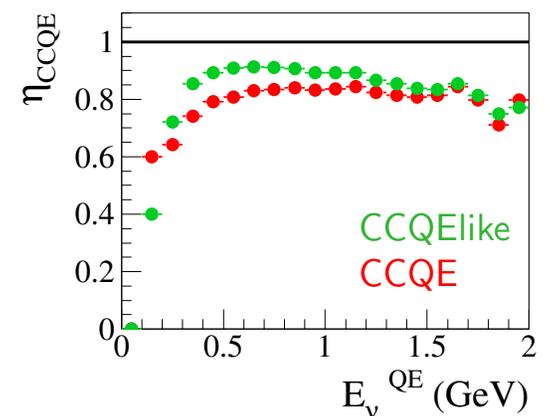
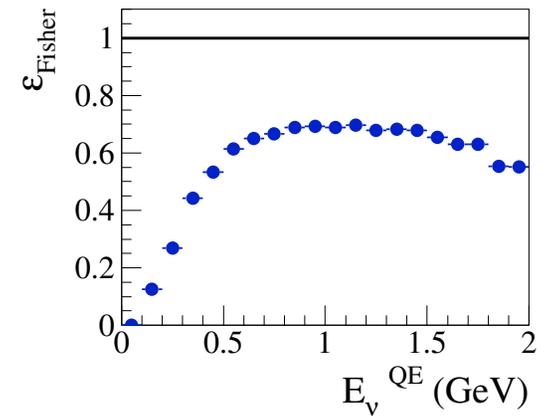
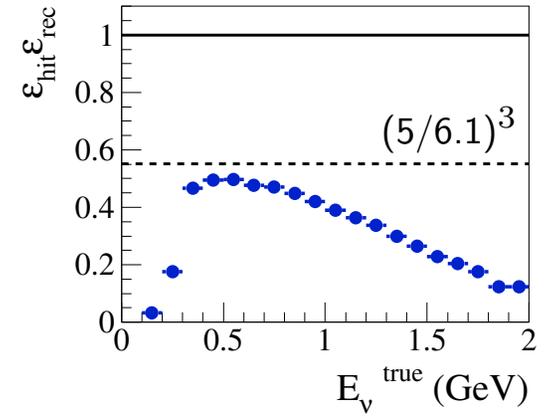
Expected Performance of the CCQE Event Selection

Hit-level and reconstruction-level selection only:

- CCQE efficiency for interactions within 6.1 m:
 $\epsilon_{\text{hit}}\epsilon_{\text{rec}} \simeq 39\%$. Fiducial volume only $\simeq (5/6.1)^3 \simeq 55\%$;
- CCQE purity: $\eta_{\text{CCQE}} \equiv \frac{N_{\text{CCQE}}}{N_{\text{all}}} \simeq 54\%$

Add event-level selection ($\text{numuCCQElike} > 0.14$):

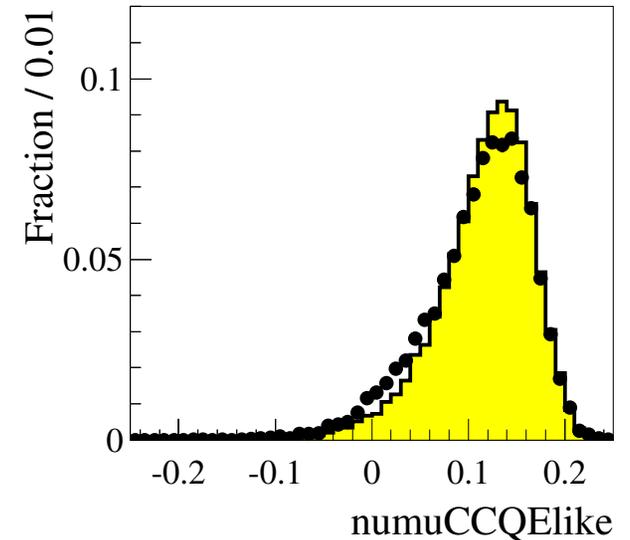
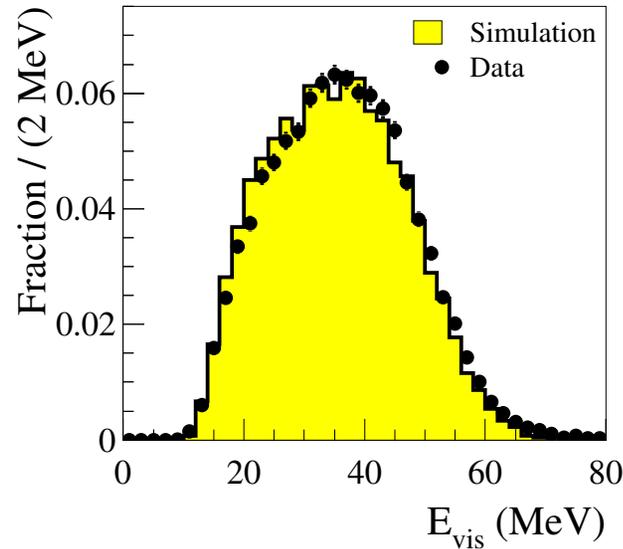
- CCQE efficiency: $\epsilon_{\text{Fisher}} \simeq 63\% \Rightarrow \epsilon_{\text{hit}}\epsilon_{\text{rec}}\epsilon_{\text{Fisher}} \simeq 25\%$
- CCQE purity: $\eta_{\text{CCQE}} \simeq 82\%$
- Irreducible non-CCQE background from events that *look like* CCQE, e.g. $\nu_{\mu}p \rightarrow \mu^{-}p\pi^{+}$ where π^{+} is absorbed in nuclear environment
- CCQElike purity: $\eta_{\text{CCQElike}} \equiv \frac{N_{\text{CCQElike}}}{N_{\text{all}}} \simeq 89\%$



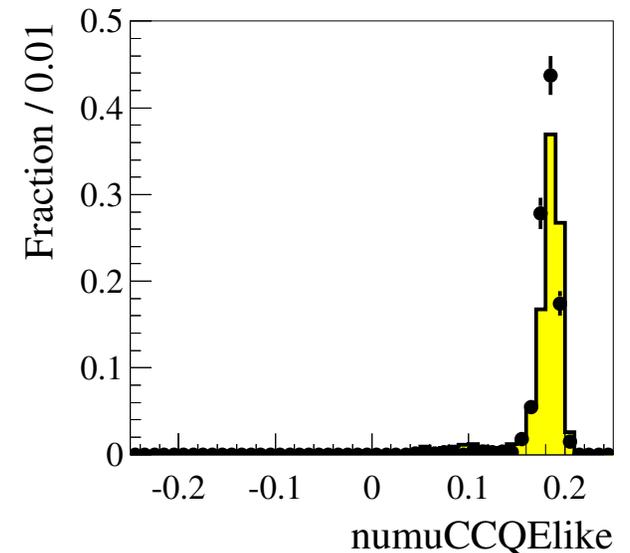
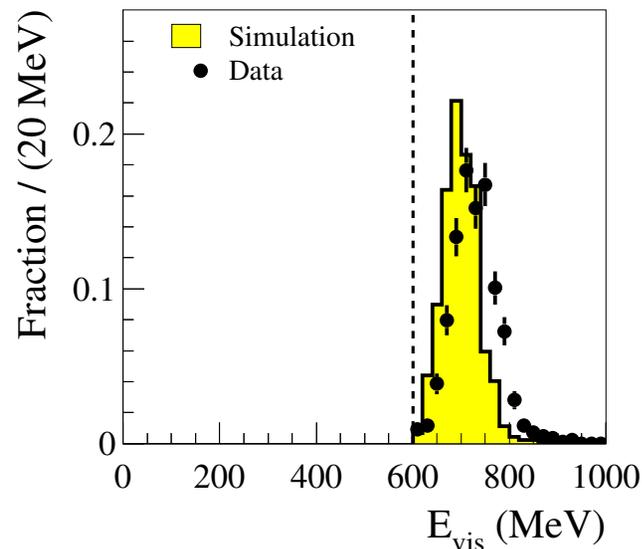
Using Calibration Samples for Validation

- Calibration samples used to validate energy reconstruction and CCQE selection
- Test detector response model. Do not depend on flux and cross-section predictions

Electron Calibration Sample

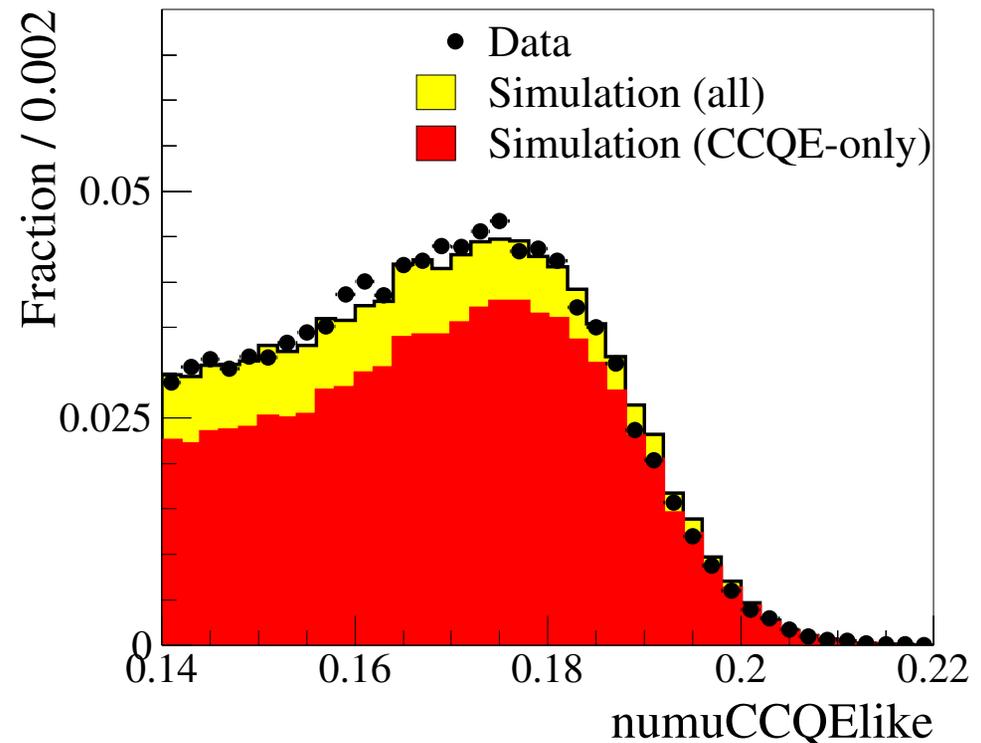


Muon Calibration Sample



The CCQE Sample Analyzed

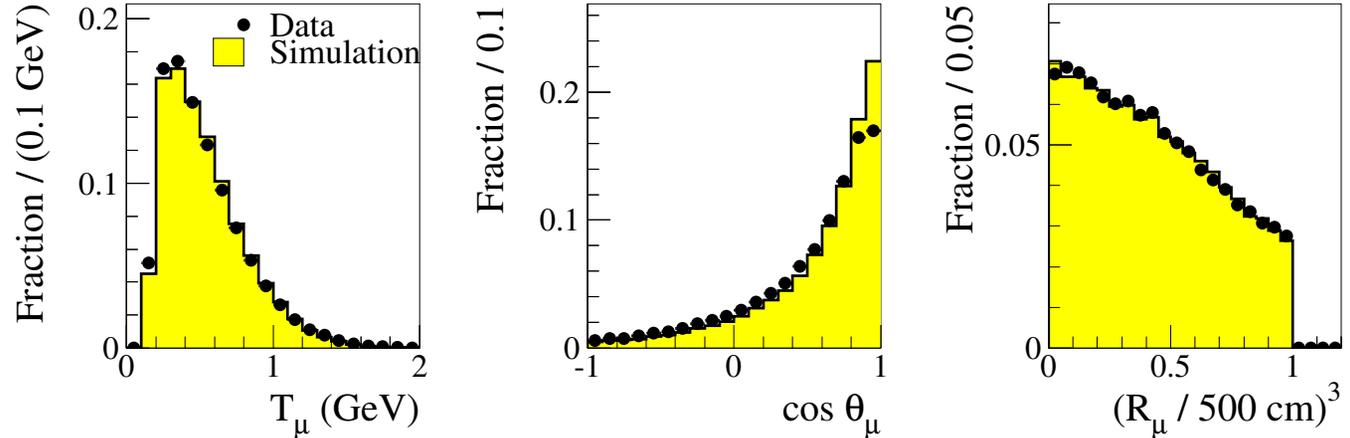
- Use neutrino data collected between December, 2002, and January, 2005
Number of protons on target: $N_{\text{pot}} = 1.9 \cdot 10^{20}$
- 55,824 CCQE neutrino candidates collected, requiring:
 - CCQE selection;
 - data of good quality (*e.g.* horn-on)..
- Compare shapes of observed and predicted distributions
⇒ look for unsimulated new physics
- Observed CCQE identification well modelled by simulations



Muon and Neutrino Properties in $\nu_\mu n \rightarrow \mu^- p$ Interactions

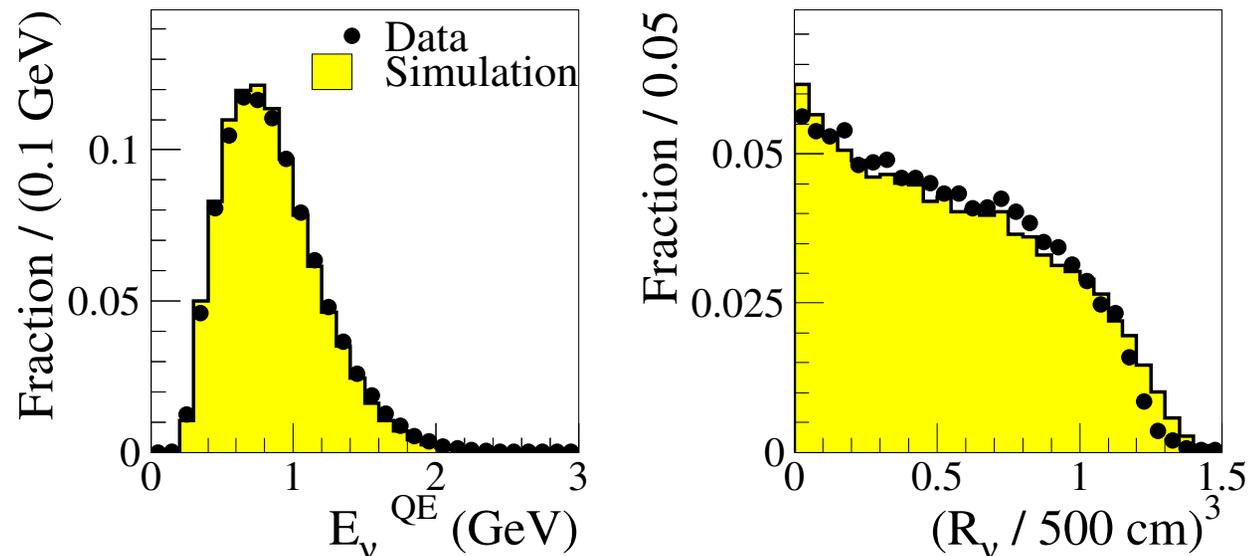
CCQE Muons:

- T_μ : muon kinetic energy
- θ_μ : angle between muon and neutrino directions
- R_μ : radial position of mean light emission point



CCQE Neutrinos:

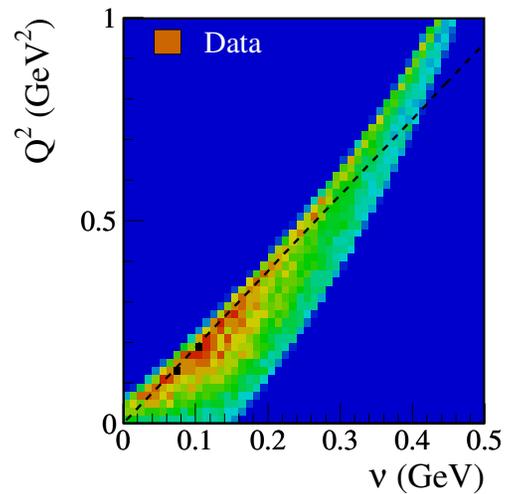
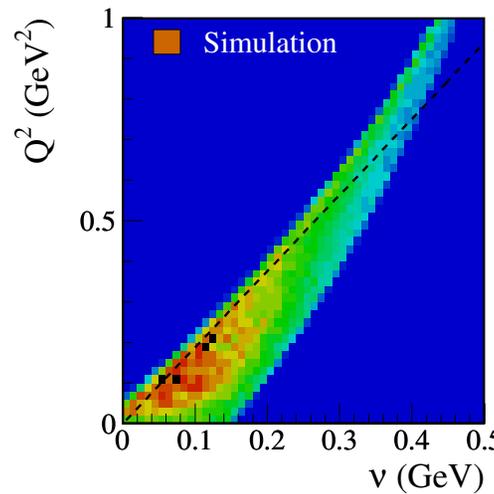
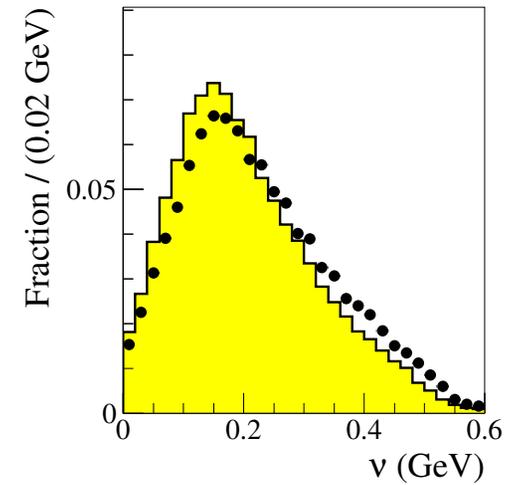
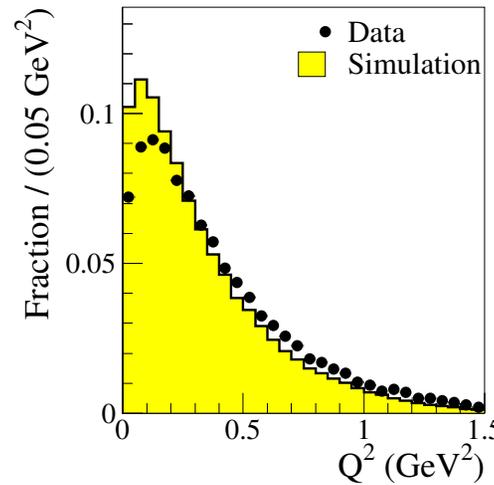
- E_ν^{QE} : neutrino energy
- R_ν : radial position of neutrino interaction vertex
- Prediction assumes no neutrino oscillations



Properties of $\nu_\mu n \rightarrow \mu^- p$ Interactions

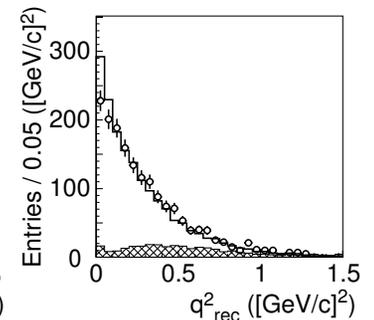
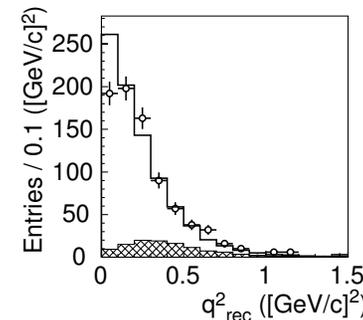
CCQE Kinematics:

- $Q^2 \equiv -(p_\nu - p_\mu)^2$
- $\nu \equiv E_\nu - E_\mu$
- Dashed line is prediction for perfect detector, no nuclear effects:
 $Q^2 = 2m_N \nu$



Rate suppression at $Q^2 \lesssim 0.15 \text{ GeV}^2 / \cos \theta_\mu \gtrsim 0.8$?

- Could be due to unsimulated nuclear effects
- Also seen by K2K experiment (hep-ex/0411038)



Computing the Sensitivity to Sterile Neutrinos via Muon Neutrino Disappearance

- Energy-shape analysis \Rightarrow look for energy-dependent distortions in the observed distribution, compared to predictions, by minimizing:

$$\chi^2(\Delta m^2, \sin^2 2\theta_{\mu\mu}, \mathbf{k}) = \sum_{\alpha, \beta} (\mathbf{N}_\alpha^{\text{obs}} - \mathbf{k} \mathbf{N}_\alpha^{\text{pred}}) (\mathbf{M}^{-1})_{\alpha\beta} (\mathbf{N}_\beta^{\text{obs}} - \mathbf{k} \mathbf{N}_\beta^{\text{pred}})$$

where:

- $\Delta m^2, \sin^2 2\theta$: oscillation parameters, k : data/prediction yield ratio parameter
- $N_\alpha^{\text{pred}} = N_\alpha^{\text{pred}}(\Delta m^2, \sin^2 2\theta_{\mu\mu})$: predicted yield in reconstructed energy bin α
- N_α^{obs} : observed yield; $\sum_\alpha N_\alpha^{\text{obs}} \simeq 5.6 \cdot 10^4$
- $M_{\alpha\beta} = M_{\alpha\beta}^{\text{stat}} + M_{\alpha\beta}^{\text{flux}} + M_{\alpha\beta}^{\text{xsec}} + M_{\alpha\beta}^{\text{det}}$: matrix describing statistical errors, and systematic errors related to flux, cross-section, and detector response predictions
- Goodness-of-fit test of no-oscillation hypothesis: vary k , fix $\sin^2 2\theta = 0$
- Oscillation parameters estimation: minimize χ^2 by varying $\Delta m^2, \sin^2 2\theta, k$
- Sensitivity study \Leftrightarrow parameter estimation with: $N_\alpha^{\text{obs}} \equiv N_\alpha^{\text{pred}}(\sin^2 2\theta_{\mu\mu} = 0)$

Systematic Error Assumptions and Expected Sensitivity

- Impact of systematic uncertainties on energy shape dominates over statistics

Flux predictions:

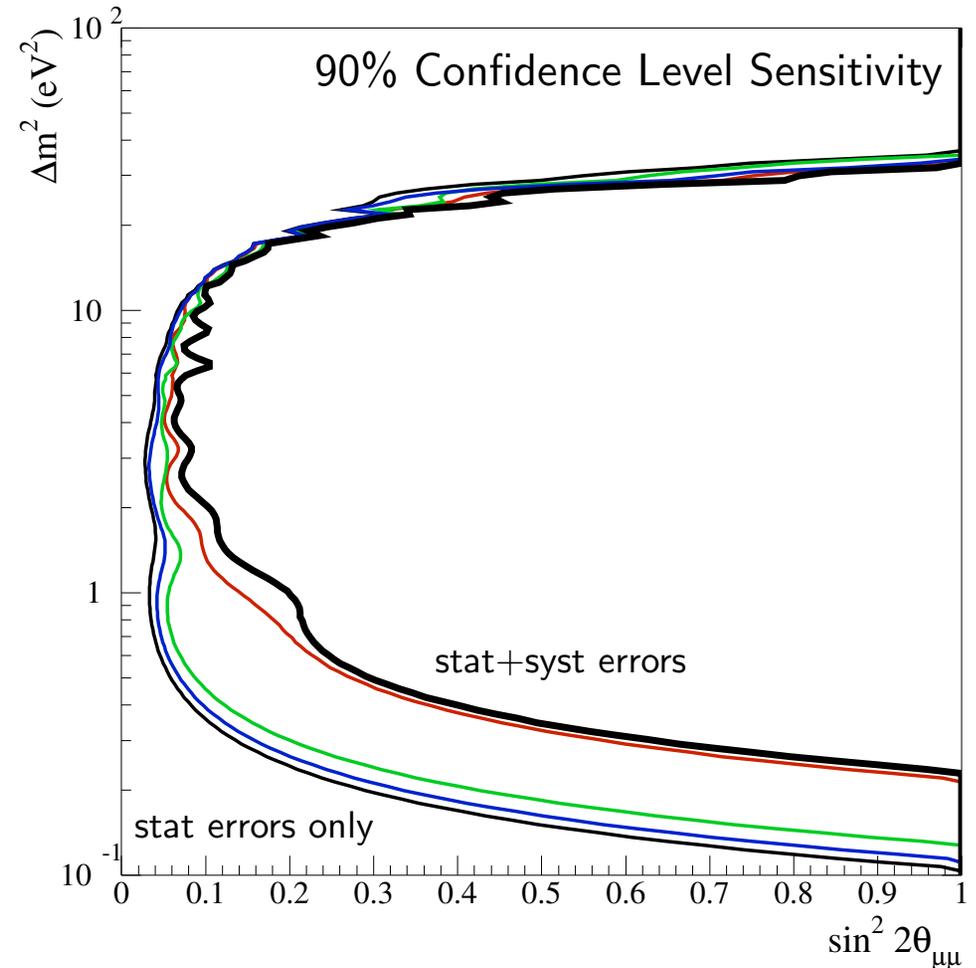
- π^+ production in $p+\text{Be} \rightarrow \pi^+ + X$
interactions: uncertainties on S-W parameters

Cross-section predictions:

- Nuclear effects: uncertainties on E_B, p_F
- CCQE form factors: uncertainty on m_A

Detector response:

- energy reconstruction: energy scale and non-linearity uncertainties estimated from muon calibration sample
- full detector response uncertainties, including effects on CCQE selection, still missing from analysis

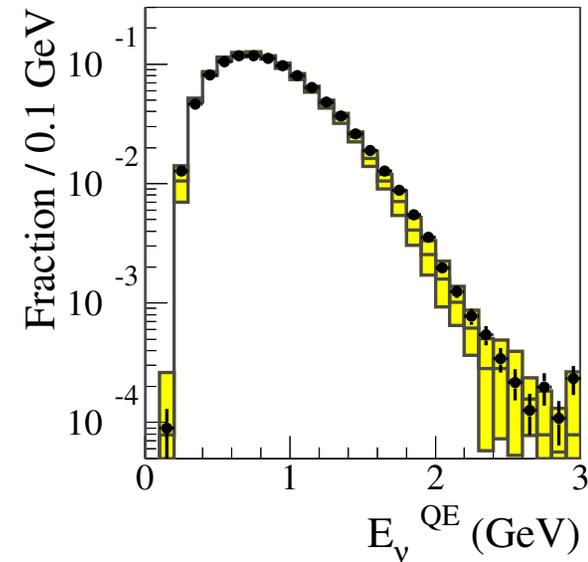
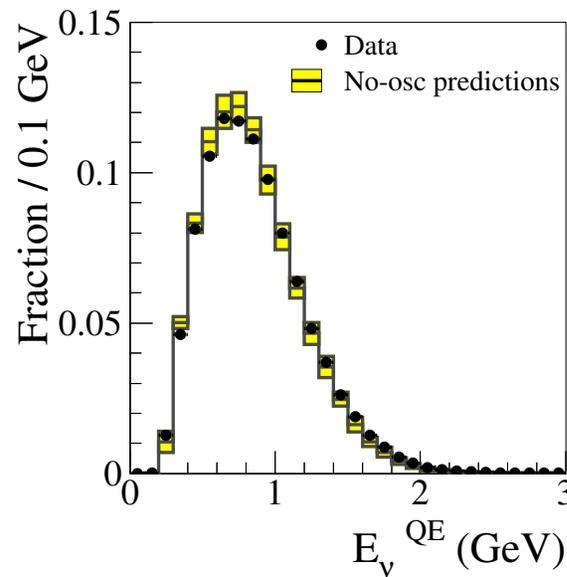


- Maximum Δm^2 range probed in energy-shape analysis: $0.1 \lesssim \Delta m^2 \lesssim 30 \text{ eV}^2$. Set by L/E distribution, statistics, energy resolution. Sensitivity to $\sin^2 2\theta_{\mu\mu} \gtrsim 0.1$

Comparing Observations with No-Oscillation Predictions

Neutrino Energy Shape:

- Boxes indicate current systematic uncertainty estimates
- Qualitative agreement between data / no-oscillation predictions

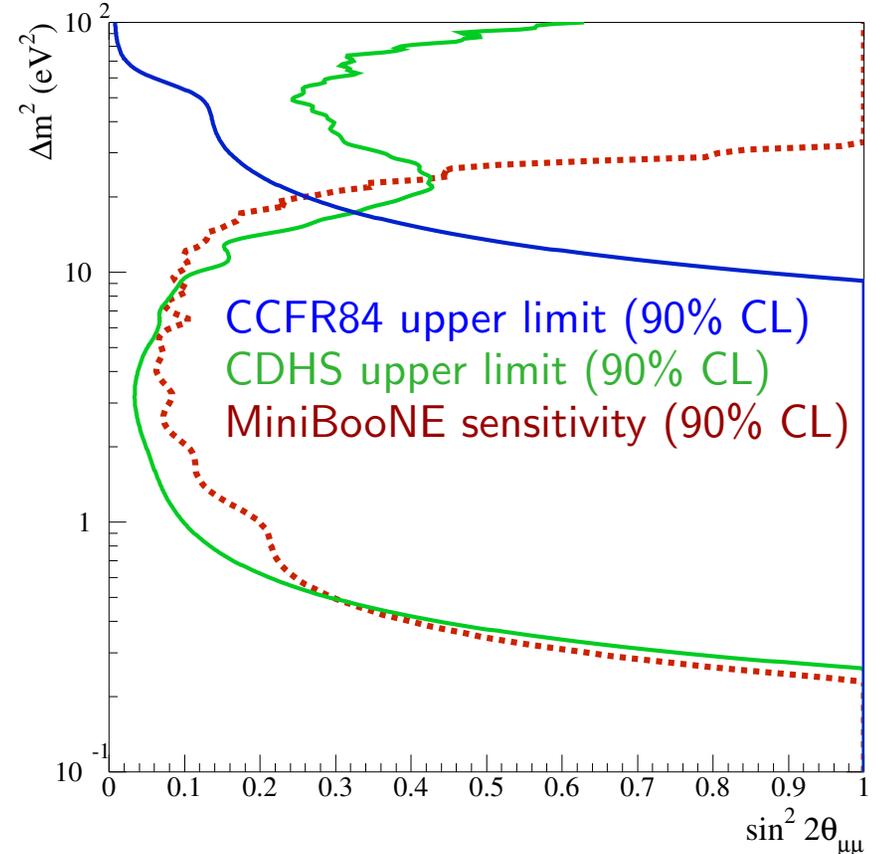


CCQE Rate Normalization:

- Flux+cross-section predictions: 17% normalization systematic uncertainty
- CCQE neutrinos-to-protons double ratio: $\frac{(N_{CCQE}/N_{pot})^{obs}}{(N_{CCQE}/N_{pot})^{pred}} = 1.60 \pm 0.17 !$
- No quantitative constraints on neutrino oscillations, because:
 - overall CCQE rate normalization not yet understood
 - full detector response systematic uncertainties still being evaluated

Toward Muon Neutrino Disappearance Results

- Compare MiniBooNE sensitivity to muon neutrino disappearance with existing upper limits, assuming that:
 - observed-to-predicted CCQE rate normalization ratio discrepancy due to currently unsimulated effect, independent of neutrino energy and interaction type (CCQE, $CC\pi^+$, $NC\pi^0$, NCE)
 - detector response systematic uncertainties affecting CCQE selection are negligible
- MiniBooNE sensitivity to $\nu_\mu \rightarrow \nu_\mu$ expected to be similar to best current limits
- HARP $p\text{-Be} \rightarrow \pi^+ + X$ results may improve sensitivity further
- Oscillation parameter regions probed by MiniBooNE include currently allowed sterile neutrino models (*e.g.* 3+1 and 3+2 models)
- Δm^2 measurement with $\simeq 20\%$ accuracy is possible, if $\nu_\mu \rightarrow \nu_s$ oscillations exist



Conclusions

Sterile neutrinos and oscillations:

- solar+atmospheric+LSND oscillations may point to the existence of light sterile neutrino species, and to active-to-sterile oscillations
- sterile neutrino models predict large muon neutrino disappearance, via $\nu_\mu \rightarrow \nu_s$

Ingredients for MiniBooNE muon neutrino disappearance search:

- External neutrino flux and cross-section predictions
- Selection of CCQE interactions, $\nu_\mu n \rightarrow \mu^- p$, and neutrino energy reconstruction

Preliminary look at CCQE interactions, and at disappearance sensitivity:

- qualitative agreement between data and predictions for no oscillations
- low- Q^2 and CCQE rate normalization puzzles
- potential to extend muon neutrino disappearance searches beyond current limits, and to confirm or refute sterile neutrino models

Outcome of This Thesis

Published Work:

- M. Sorel and J. M. Conrad, “*Supernova neutrinos and the LSND Evidence for Neutrino Oscillations,*” Phys. Rev. D **66**, 033009 (2002) [arXiv:hep-ph/0112214]
- M. Sorel, J. M. Conrad and M. Shaevitz, “*A combined analysis of short-baseline neutrino experiments in the (3+1) and (3+2) sterile neutrino oscillation hypotheses,*” Phys. Rev. D **70**, 073004 (2004) [arXiv:hep-ph/0305255]

Publications in Preparation ($\simeq 6$ months):

- A. Aguilar-Arevalo, V. Barger, J. M. Conrad, M. Shaevitz, M. Sorel, K. Whisnant, “*CP Violation in (3+2) Sterile Neutrino Models*”
- MiniBooNE Collaboration, “*The MiniBooNE Neutrino Focusing Horn*”
- MiniBooNE Collaboration, “*Neutrino Flux Predictions for the MiniBooNE Experiment*”
- MiniBooNE Collaboration, “*Search for Muon Neutrino Disappearance with the MiniBooNE Experiment*”

Thank You!

- MiniBooNE Collaboration



- Columbia Neutrino Group

Backups follow

Chapter 1

Short-Baseline Oscillation Results

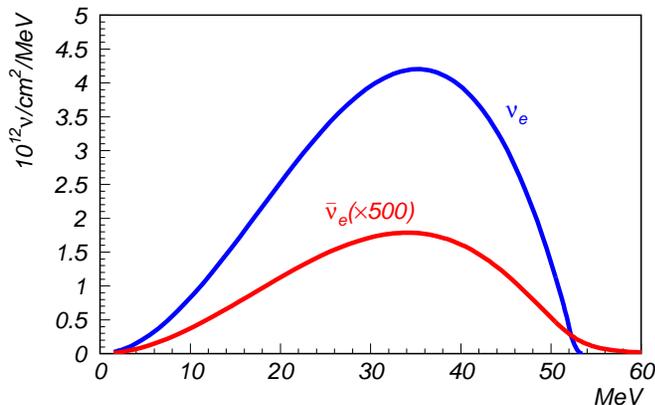
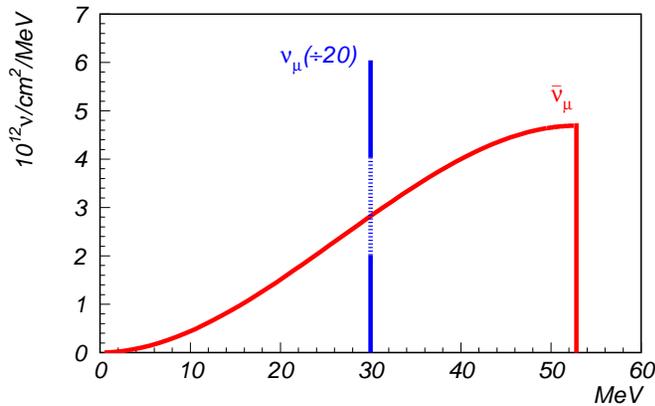
- List of most sensitive short- and medium-baseline neutrino oscillation searches in various oscillation channels
- Δm^2 is in eV^2 , and low Δm^2 reach and $\sin^2 2\theta$ constraints are given at the 90% confidence level:

Channel	Experiment	Optimal Δm^2	Low Δm^2 Reach	$\sin^2 2\theta$ Constraint	
				High Δm^2	Optimal Δm^2
$\nu_\mu \rightarrow \nu_e$	LSND	$2 \cdot 10^0$	$3 \cdot 10^{-2}$	$[2.5 - 3.8] \cdot 10^{-3}$	$[1.2 - 3.2] \cdot 10^{-3}$
	KARMEN	$3 \cdot 10^0$	$6 \cdot 10^{-2}$	$< 1.7 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
	NOMAD	$3 \cdot 10^1$	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \rightarrow \nu_\mu$	Bugey	$6 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$< 1.4 \cdot 10^{-1}$	$< 1.3 \cdot 10^{-2}$
	CHOOZ	$6 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-1}$	$< 5 \cdot 10^{-2}$
$\nu_\mu \rightarrow \nu_\mu$	CCFR84	$9 \cdot 10^2$	$6 \cdot 10^0$	none	$< 2 \cdot 10^{-1}$
	CDHS	$3 \cdot 10^0$	$3 \cdot 10^{-1}$	none	$< 5.3 \cdot 10^{-1}$
$\nu_\mu \rightarrow \nu_\tau$	NOMAD	$1 \cdot 10^2$	$7 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-4}$	$< 2.5 \cdot 10^{-4}$
	CHORUS	$6 \cdot 10^1$	$5 \cdot 10^{-1}$	$< 6.8 \cdot 10^{-4}$	$< 4.5 \cdot 10^{-4}$
$\nu_e \rightarrow \nu_\tau$	NOMAD	$1 \cdot 10^2$	$6 \cdot 10^0$	$< 1.5 \cdot 10^{-2}$	$< 1.1 \cdot 10^{-2}$
	CHORUS	$9 \cdot 10^1$	$7 \cdot 10^0$	$< 5.1 \cdot 10^{-2}$	$< 4 \cdot 10^{-2}$

LSND Experiment

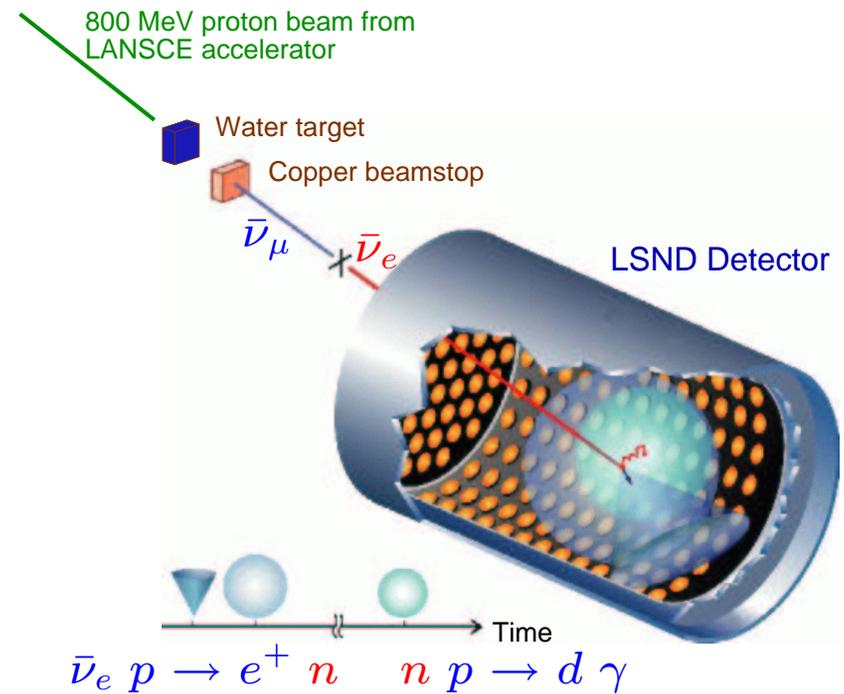
The neutrino source:

- $\bar{\nu}_\mu$ from: $\pi^+ \rightarrow \mu^+ \nu_\mu$
 $\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$
- $E_\nu = 20\text{-}53 \text{ MeV}$, $L_\nu = 25\text{-}35 \text{ m}$
- Almost no $\bar{\nu}_e$ at source



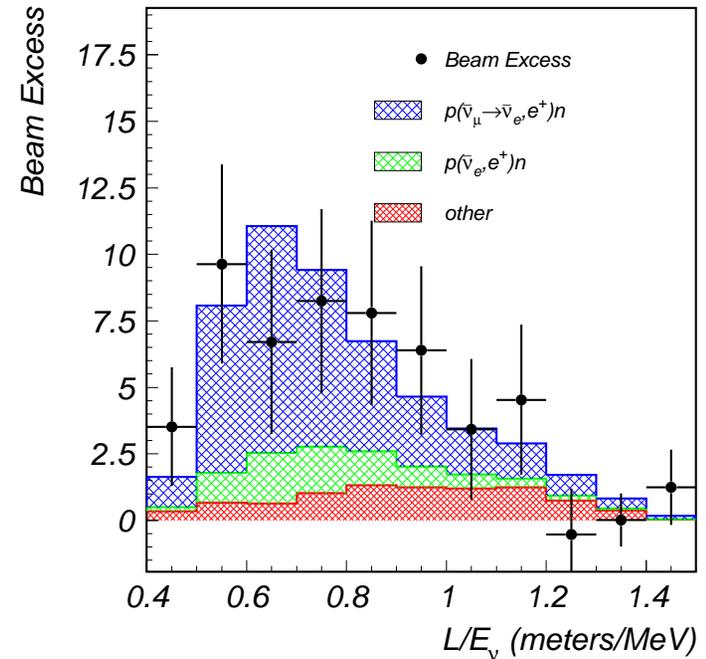
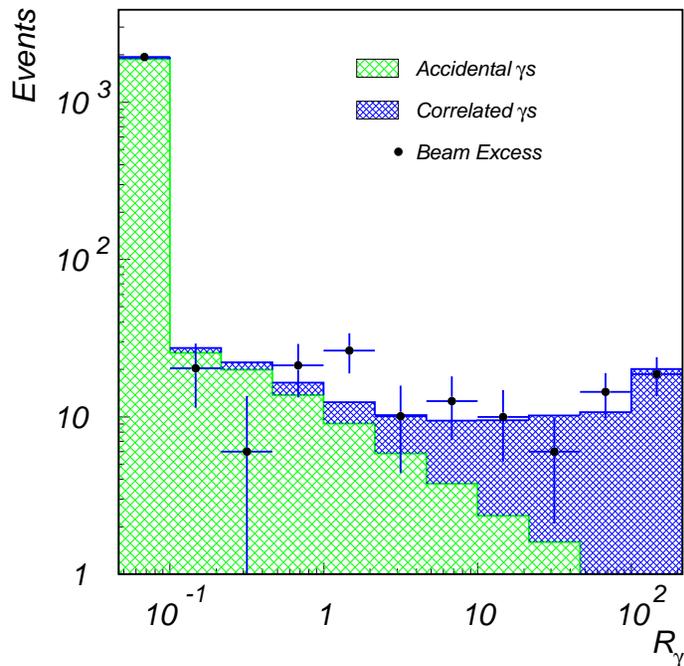
The detector:

- Liquid scintillator detects both Cherenkov and scintillation light. For $\bar{\nu}_e p \rightarrow e^+ n$:
- Č+scintillation light from e^+
- Scintillation light from n capture



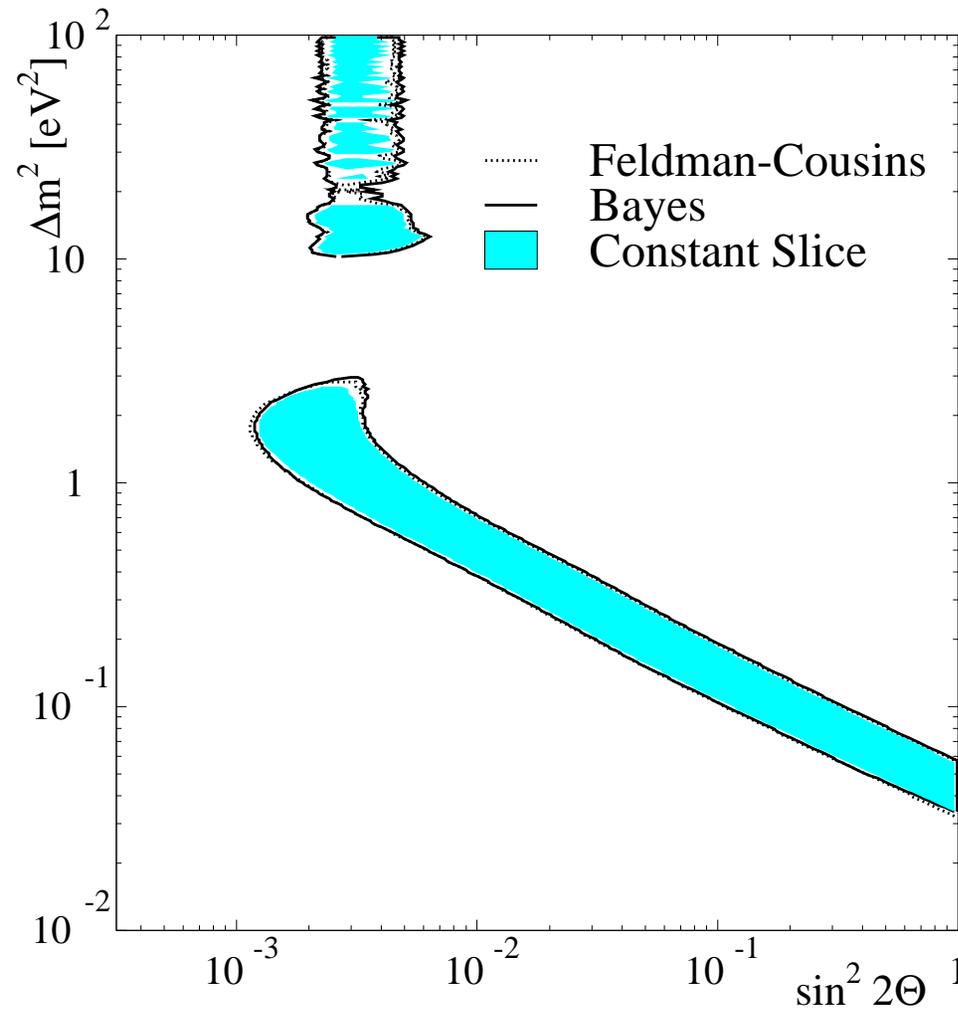
LSND Result

- Excess of candidate $\bar{\nu}_e$ events
- R_γ parameter defines likelihood that γ is correlated to e^+ . By fitting R_γ :
- $87.9 \pm 22.4 \pm 6.0$ excess (3.8σ)
- $\langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle = (0.264 \pm 0.067 \pm 0.045)\%$
- Clean sample with $R_\gamma > 10$ cut
- L_ν/E_ν distribution of the excess agrees well with oscillation hypothesis
- Backgrounds in green, red
- Fit to oscillation hypothesis in blue



LSND Allowed Parameter Space (90% CL)

- LSND is mostly a “counting experiment”: little spectral information
- Large degeneracy in $(\sin^2 2\theta, \Delta m^2)$ space

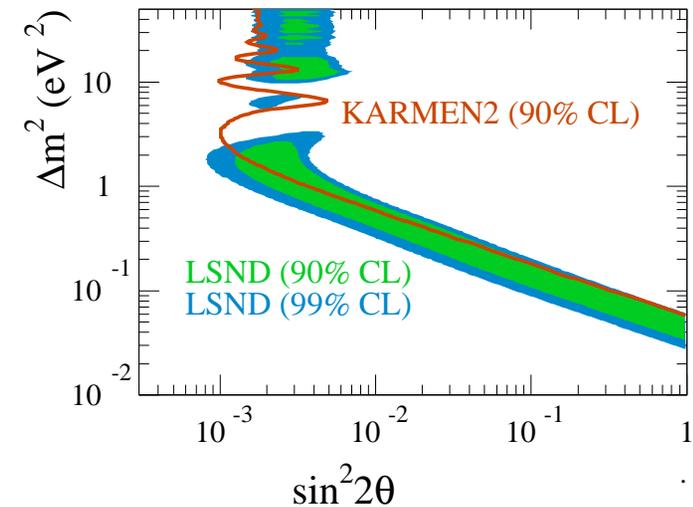


KARMEN Constraints on LSND Oscillations

- KARMEN and LSND: similar neutrino fluxes, detection principle, baseline
- KARMEN: consistent with SM expectations \Rightarrow constraints on LSND?

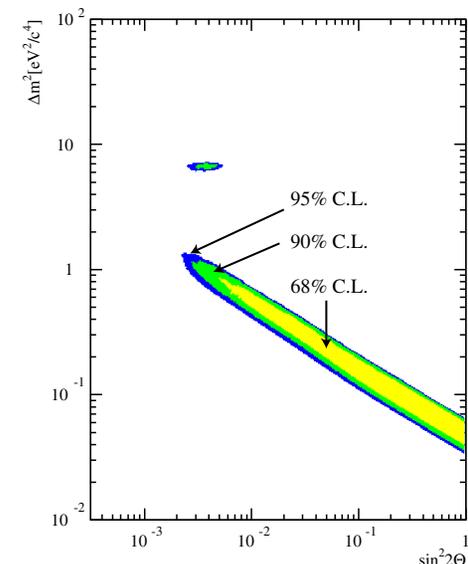
- KARMEN-only:

- Only part of the LSND oscillation parameter space can be excluded by KARMEN



- KARMEN+LSND:

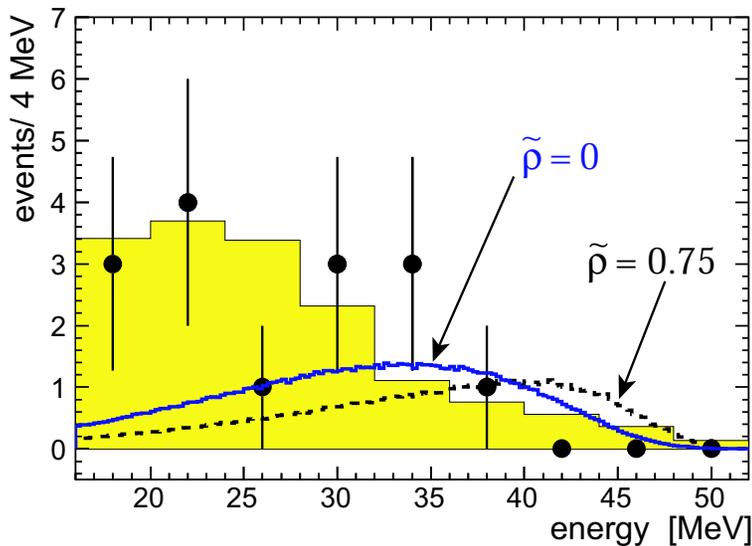
- Two results are compatible, assuming oscillations
- Joint analysis is justified, and allowed space is similar to LSND-only region (Church *et al.*, hep-ex/0203023)



KARMEN Constraints on LSND Exotic Decays

- Alternatives to oscillations to explain the LSND signal?
- Lepton-flavor violating decay mode was suggested: $\mu^+ \rightarrow e^+ \bar{\nu}_e \begin{pmatrix} - \\ \nu \end{pmatrix}$
- LF number violating decay is allowed in many extensions of the SM
- Expected $\bar{\nu}_e$ energy spectrum from decay ($x \equiv E_\nu / E_{max}$, $E_{max} = 52.8$ MeV):

$$\mathbf{N(x)dx} \propto \mathbf{x^2[3(1 - x) + \frac{2}{3}\tilde{\rho}(4x - 3)]dx}$$

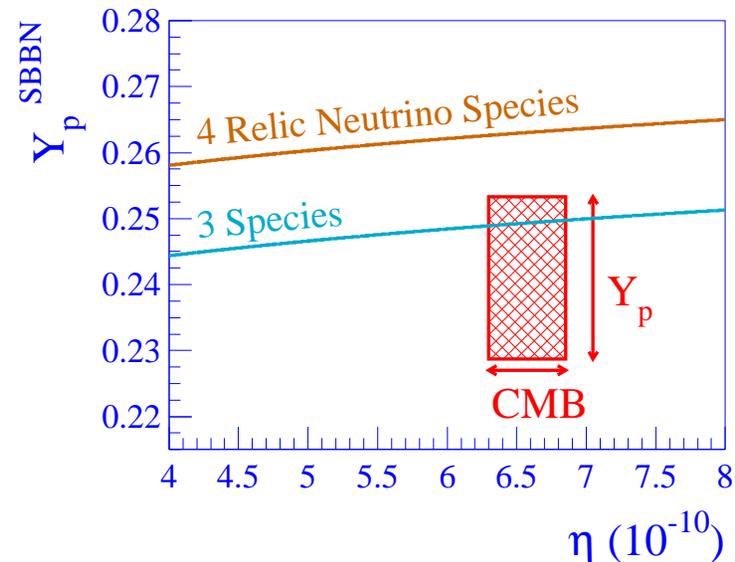


- KARMEN limit on $\mu^+ \rightarrow e^+ \bar{\nu}_e \begin{pmatrix} - \\ \nu \end{pmatrix}$ branching ratio: $BR_{\text{KARMEN}} < 0.9 \cdot 10^{-3}$ (90% CL)
- LSND signal would require: $1.9 \cdot 10^{-3} < BR_{\text{LSND}} < 4.0 \cdot 10^{-3}$ (90% CL)
- $\mu^+ \rightarrow e^+ \bar{\nu}_e \begin{pmatrix} - \\ \nu \end{pmatrix}$ cannot explain LSND signal

Cosmology and massive neutrinos

- Standard cosmology (Λ CDM) assumes three active, massless, neutrinos, and no lepton asymmetry
- Observations \sim agree with predictions of standard cosmology:
 - Primordial Helium (and Deuterium) abundance
 - Amplitude and shape of large scale power spectrum
- In the simplest picture, massive sterile neutrinos with significant mixing to active neutrinos are expected to alter both these predictions, in disagreement with data

Example: primordial He/H ratio Y_p as a function of the baryon-to-photon ratio
(Di Bari, astro-ph/0302433,
Abazajian, astro-ph/0205238)



Cosmology and massive sterile neutrinos (2)

- Predictions of standard cosmology assume that sterile neutrino species are present in the early Universe in the same abundances as the active species
- Several mechanisms have been proposed that would suppress the (sterile) neutrino abundances in cosmology, for example:
 - primordial lepton asymmetries;
 - additional neutrino interactions;
 - low reheating temperature scenarios.
- Cosmological constraints on sterile neutrinos should be taken with caution, and in any case complemented with terrestrial experiments (where the interpretation of data is easier)

Chapter 2

Supernova Neutrinos and the Neutrino Mass Hierarchy

- Matter effects play a role in the propagation of supernova neutrinos. In this case, neutrino oscillations are sensitive to the neutrino mass hierarchy
- Electron neutrinos from the SN1987A supernova explosion have been observed in the Kamiokande and IMB detectors (\Rightarrow Nobel prize!)
- Electron neutrino energy spectrum on Earth provides constraints on $\nu_{\mu,\tau} \rightarrow \nu_e$ transitions, and on the neutrino mass hierarchy and mixings

Model	SN1987A constraint on LSND region (99% CL)
Normal (1 + 1)	partially excluded
LSND-inverted (1 + 1)	excluded
Normal (2 + 1)	unconstrained
LSND-inverted (2 + 1)	excluded
Normal (2 + 2)	partially excluded
LSND-inverted (2 + 2)	excluded
Normal (3 + 1)	partially excluded
LSND-inverted (3 + 1)	excluded

Combined analysis of SBL experiments

- Short-baseline experiments on
 - ν_μ disappearance (CCFR84, CDHS)
 - $\bar{\nu}_e$ disappearance (Bugey, CHOOZ)
 - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance (LSND, KARMEN, NOMAD)

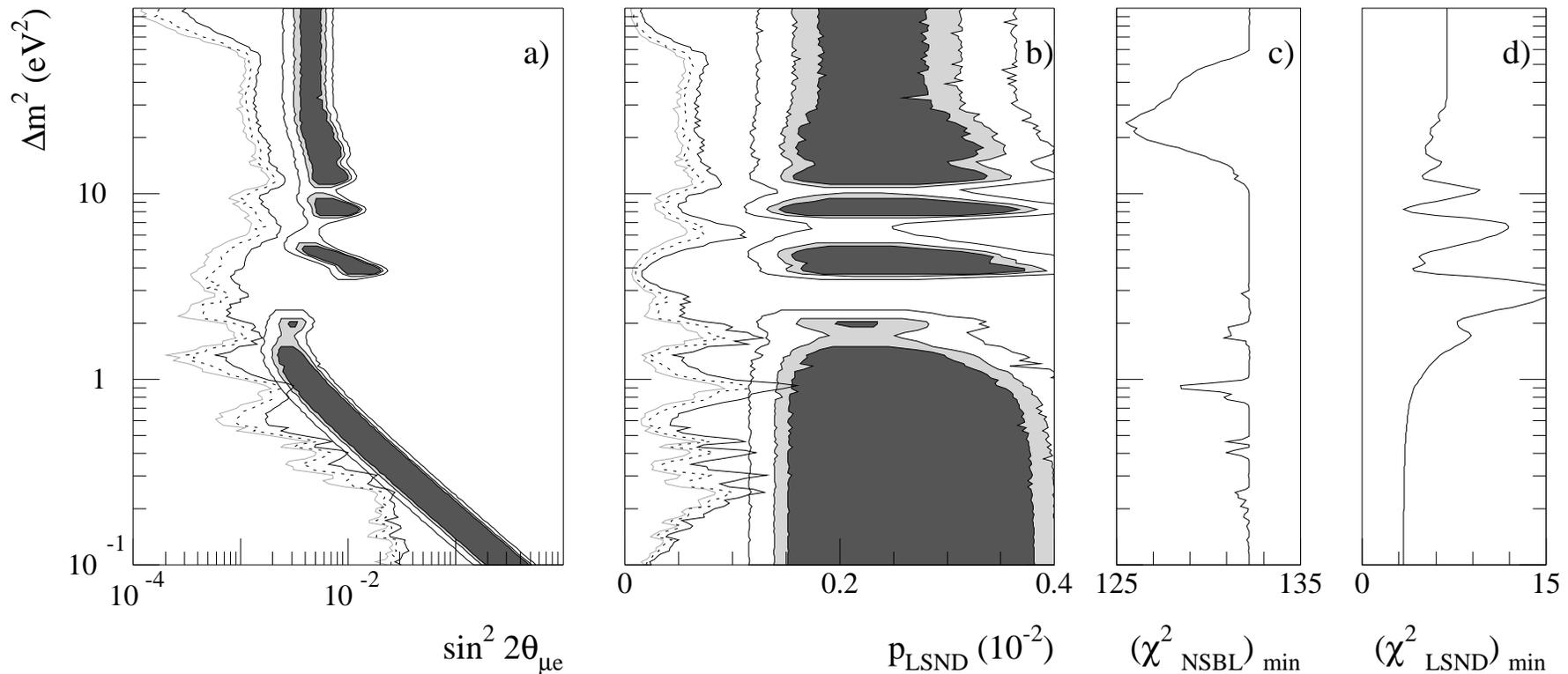
probe the same Δm^2 range and the same matrix elements:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \dots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} & \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ \dots & & & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

- Only LSND demands $U_{e4}U_{\mu4} \neq 0$, or $U_{e5}U_{\mu5} \neq 0$, etc.
- Is LSND consistent with the upper limits on active-sterile mixing at high Δm^2 derived by the null short-baseline experiments (NSBL)?
- NSBL = Bugey + CHOOZ + CCFR84 + CDHS + KARMEN + NOMAD

Are (3+1) Sterile Neutrino Models Excluded?

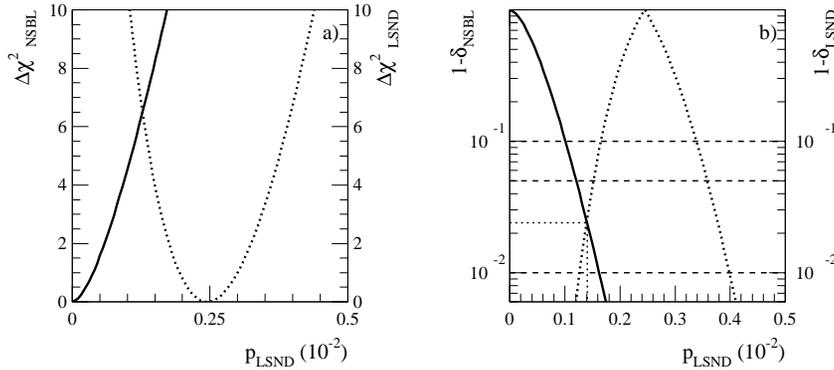
- Use null short-baseline (NSBL) results on $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$, to constrain LSND $\nu_\mu \rightarrow \nu_e$
- Why $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$? In (3+1) models: $\sin^2 2\theta_{\mu e} \simeq \frac{1}{4} \sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$
- $p_{\text{LSND}} \equiv \langle p(\nu_\mu \rightarrow \nu_e) \rangle$: oscillation probability averaged over LSND L/E distribution
- Curves/regions shown at 90%, 95%, and 99% confidence level. (3+1) models are **marginally compatible** with SBL data



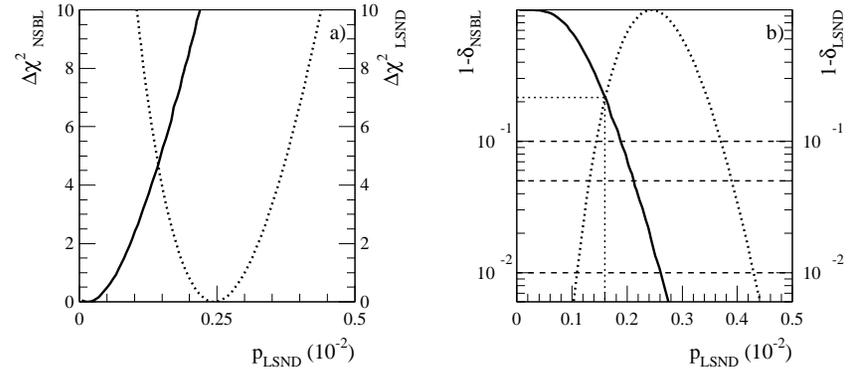
(3+2) Sterile Neutrino Models

- (3+2) sterile neutrino models **fit existing short-baseline data significantly better** than (3+1) models. In plots below, δ indicates confidence level value

(3+1) Model



(3+2) Model



- Six parameters probed (no CP viol.):

$$\Delta m_{41}^2, U_{e4}, U_{\mu 4}, \Delta m_{51}^2, U_{e5}, U_{\mu 5}$$

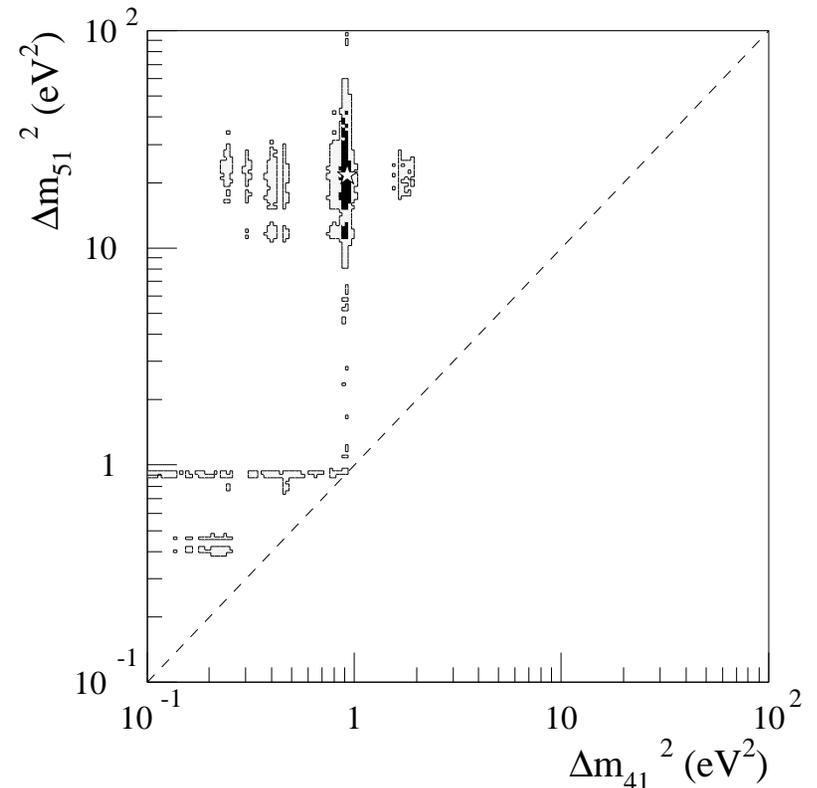
⇒ more than one Δm^2 contributes to oscillation probability

- LSND+NSBL best-fit:

$$\Delta m_{41}^2 = 0.92 \text{ eV}^2, U_{e4} = 0.121, U_{\mu 4} = 0.204$$

$$\Delta m_{51}^2 = 22 \text{ eV}^2, U_{e5} = 0.036, U_{\mu 5} = 0.224$$

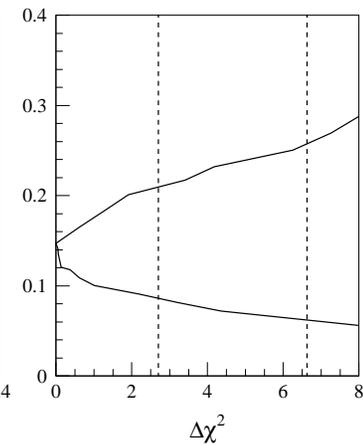
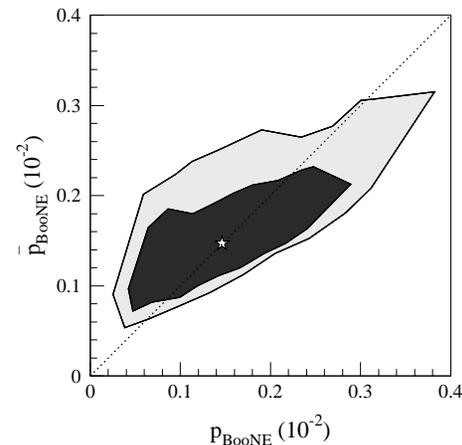
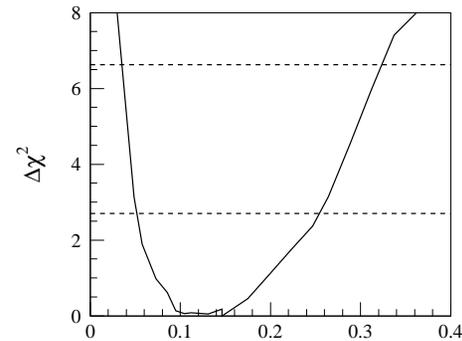
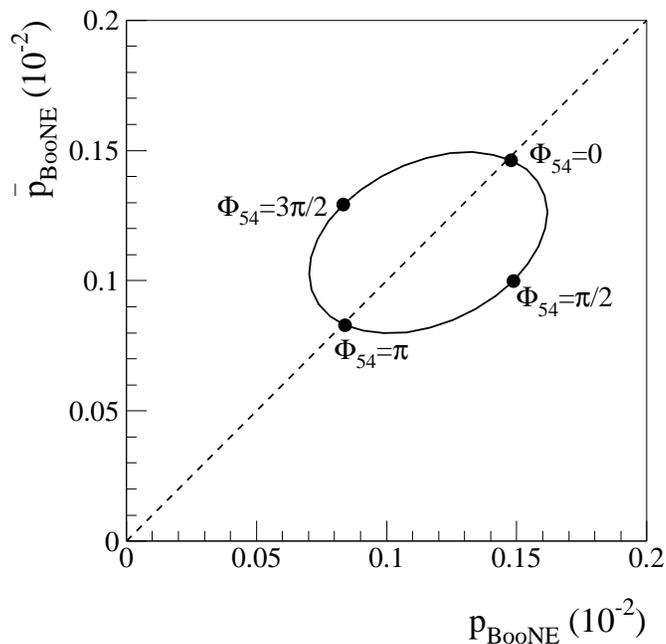
- Plot shows allowed ranges in $(\Delta m_{41}^2, \Delta m_{51}^2)$ space for (3+2) models, from a combined NSBL+LSND analysis



CP-Violation in (3+2) Sterile Neutrino Models

- Active-sterile neutrino oscillations at Δm_{LSND}^2 , and involving at least two sterile neutrinos, would open the possibility for leptonic CP-violation at short baselines
- SBL CP violation could significantly alter the expectations for oscillations in MiniBooNE ν running mode, based on the LSND $\bar{\nu}$ signal indication
- $\bar{p}_{\text{BooNE}}^{(-)} \equiv \langle p(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}) \rangle$: oscillation probability averaged over MiniBooNE L/E distribution, in neutrino (antineutrino) running mode

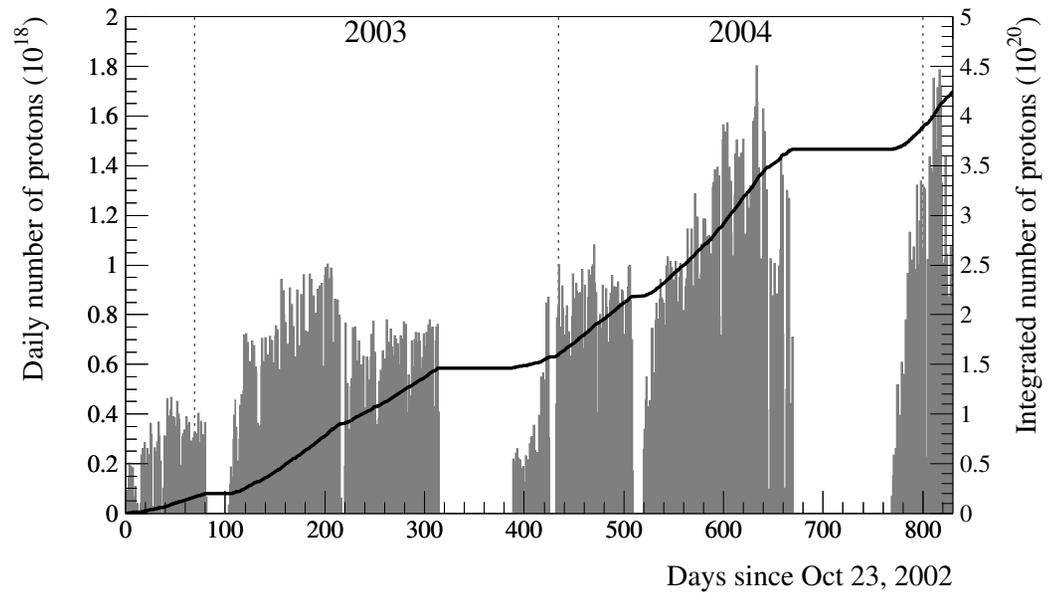
$$\phi_{54} \equiv \arg(\mathbf{U}_{\mu 5}^* \mathbf{U}_{e 5} \mathbf{U}_{\mu 4} \mathbf{U}_{e 4}^*)$$



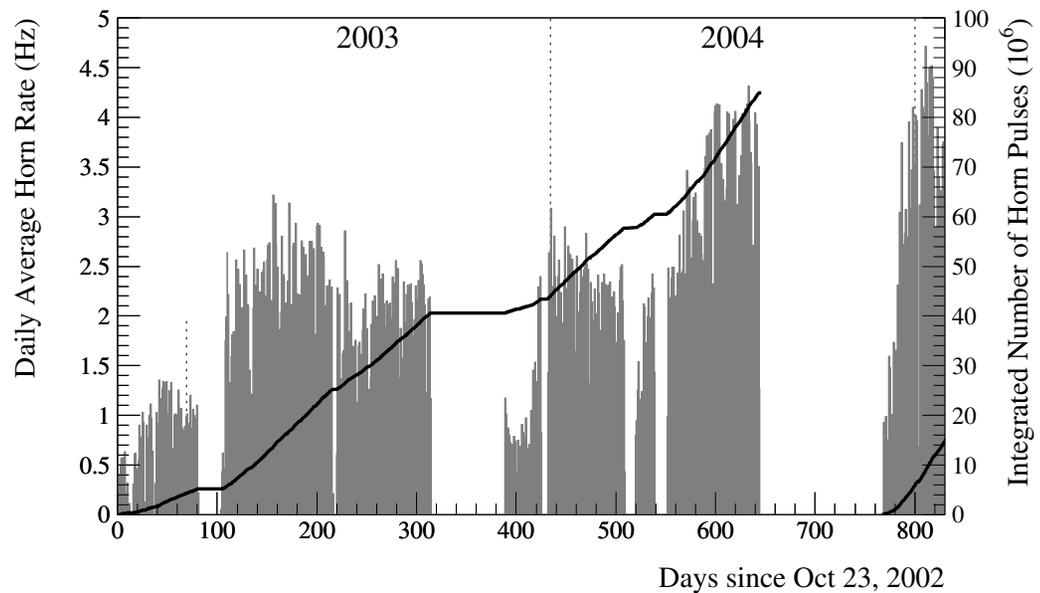
Chapter 3

Performance of MiniBooNE Neutrino Beamline

- More than $4 \cdot 10^{20}$ protons on target collected so far



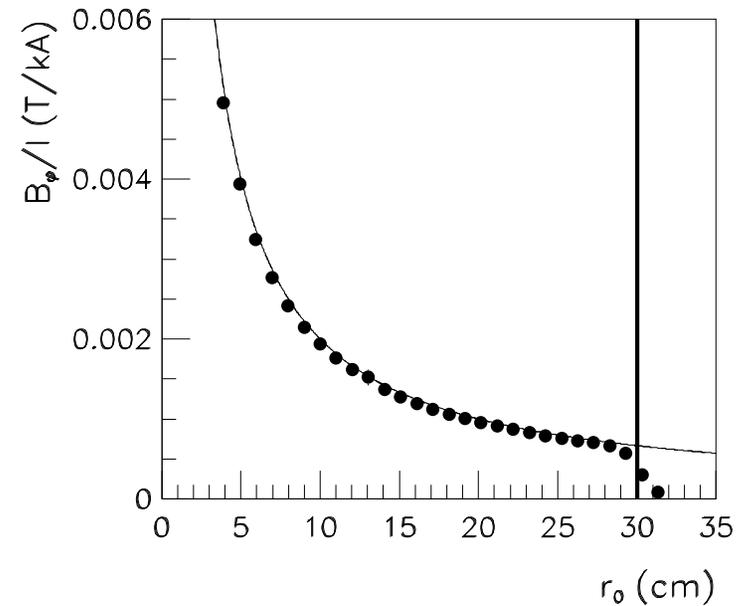
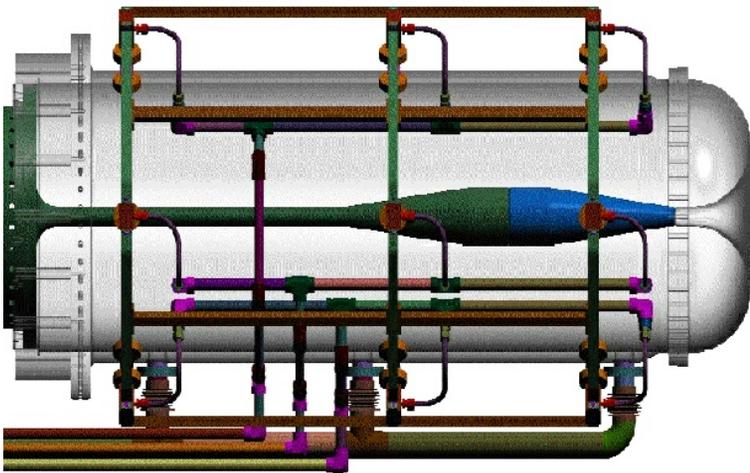
- Two horns installed so far have been pulsed more than 10^8 times (unprecedented)



MiniBooNE Neutrino Focusing Horn

- Magnetic field between horn inner and outer conductors:

$$B_{\phi} = \frac{\mu_0 I_0}{2\pi r}, \quad B_r = B_z = 0$$

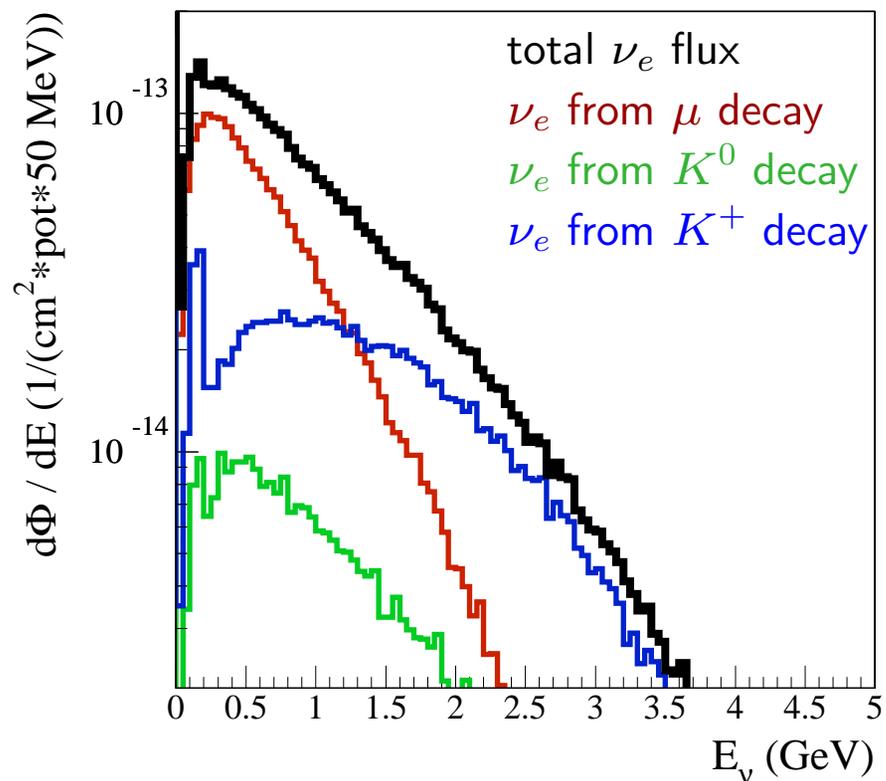


- Measured neutrino interaction rate increase due to π^+ horn focusing: factor of 6

Chapter 4

MiniBooNE Electron Neutrino Fluxes

- For $\nu_\mu \rightarrow \nu_e$ search, important background is intrinsic ν_e background in the beam ($\simeq 0.6\%$):



- Internal cross-checks:
 - ν_e from K^+ decays from high p_t muons in LMC
 - ν_e from μ^+ decays from ν_μ data and variable-length decay region

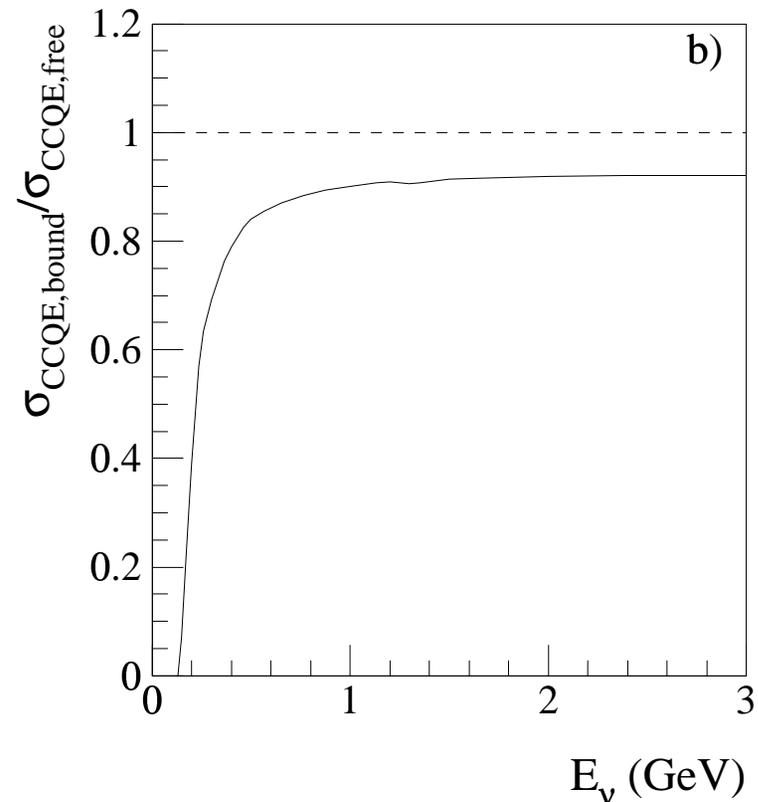
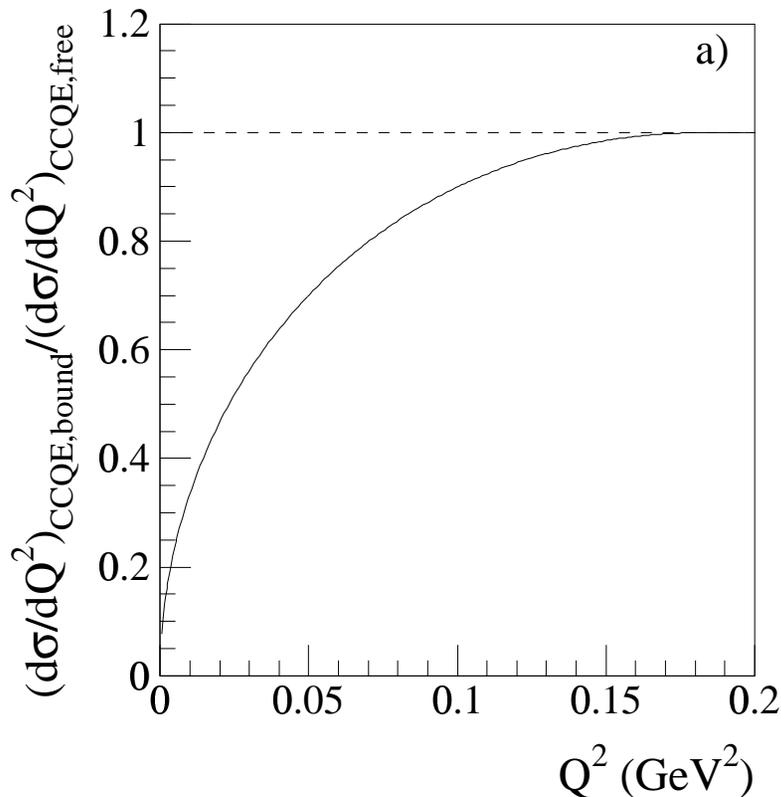
Chapter 5

NUANCE Rate Predictions

Interaction Type		Fraction (%)
Quasi-Elastic	CC: $\nu_\mu n \rightarrow \mu^- p$	39.9
	NC: $\nu_\mu N \rightarrow \nu_\mu N$	16.3
	CC/NC	56.2
Resonant single π	CC: $\nu_\mu N \rightarrow \mu^- N\pi$	26.4
	NC: $\nu_\mu N \rightarrow \nu_\mu N\pi$	9.3
	CC/NC	35.7
Coherent single π	CC: $\nu_\mu A \rightarrow \mu^- \pi^+ A$	2.5
	NC: $\nu_\mu A \rightarrow \nu_\mu \pi^0 A$	1.5
	CC/NC	4.0
Resonant multi π	CC: $\nu_\mu N \rightarrow \mu^- \Delta\pi, \mu^- N(\rho/\eta), \mu^- (\Lambda/\Sigma)K, \mu^- N\pi\pi$	2.0
	NC: $\nu_\mu N \rightarrow \nu_\mu \Delta\pi, \nu_\mu N(\rho/\eta), \nu_\mu (\Lambda/\Sigma)K, \nu_\mu N\pi\pi$	0.8
	CC/NC	2.8
DIS	CC: $\nu_\mu N \rightarrow \mu^- X$	0.8
	NC: $\nu_\mu N \rightarrow \nu_\mu X$	0.3
	CC/NC	1.1
Δ radiative decay	CC: $\nu_\mu N \rightarrow \mu^- N\gamma$	<0.1
	NC: $\nu_\mu N \rightarrow \nu_\mu N\gamma$	0.1
	CC/NC	0.1

Low- Q^2 Pauli Suppression

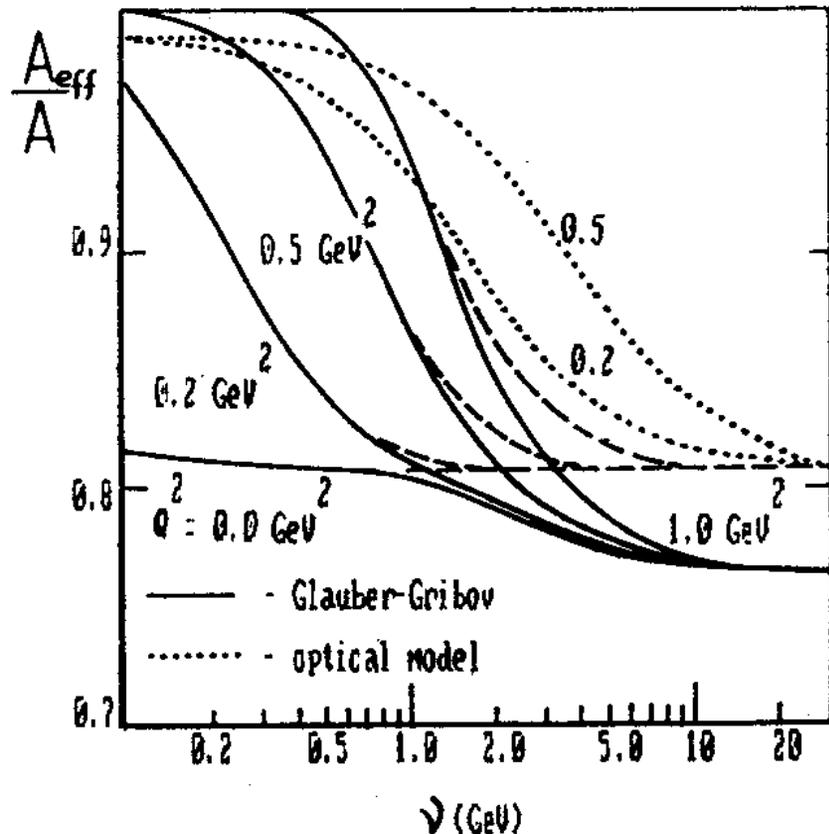
- Low- Q^2 CCQE neutrino interactions are suppressed because of Pauli exclusion principle: momentum state of final state proton needs not be occupied by other proton in the nucleus
- In Fermi gas nuclear model, Pauli blocking of the CCQE cross-section, as a function of Q^2 and E_ν , can be derived analytically:



Nuclear Shadowing

- First suggested by Bell in 1964 that neutrino-induced interactions might be less probable than what expected from nucleon counting
- First evidence: BEBC in 1988
- Large effects expected at low Q^2 and high ν

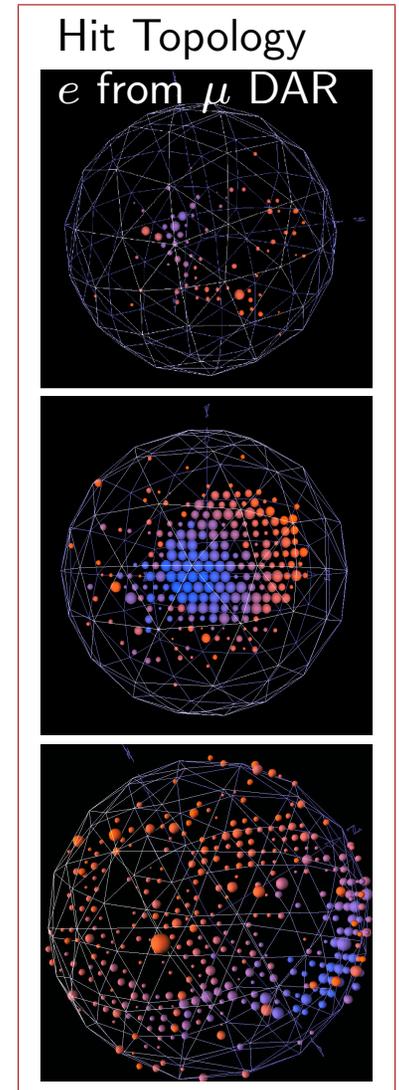
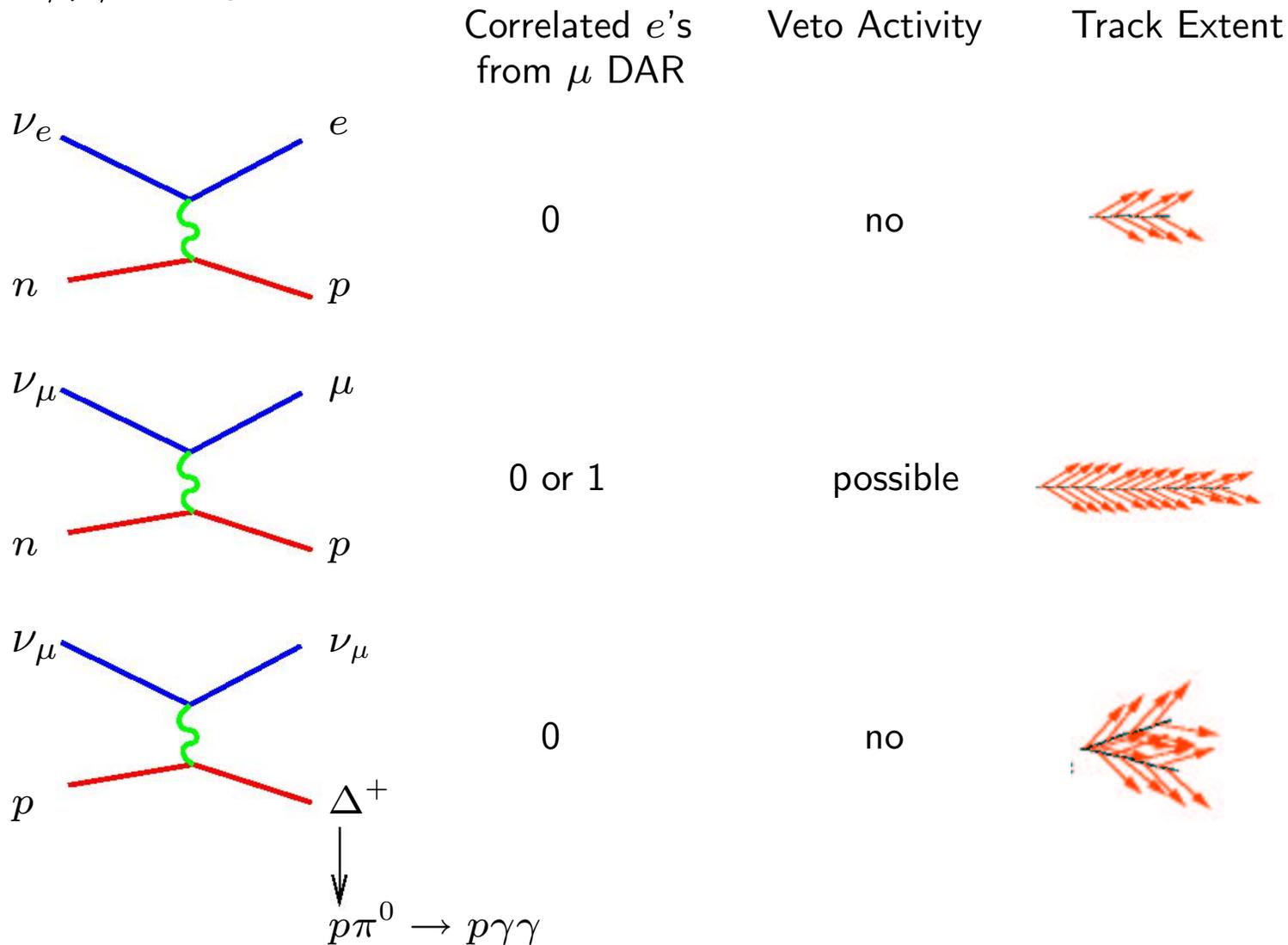
B. Kopeliovich, “Nuclear Opacity
for Neutrinos at Small Q^2 ”
Phys. Lett. **B227**, 461 (1989)



Chapter 6

MiniBooNE Particle ID

- $e/\mu/\pi^0$ separation:

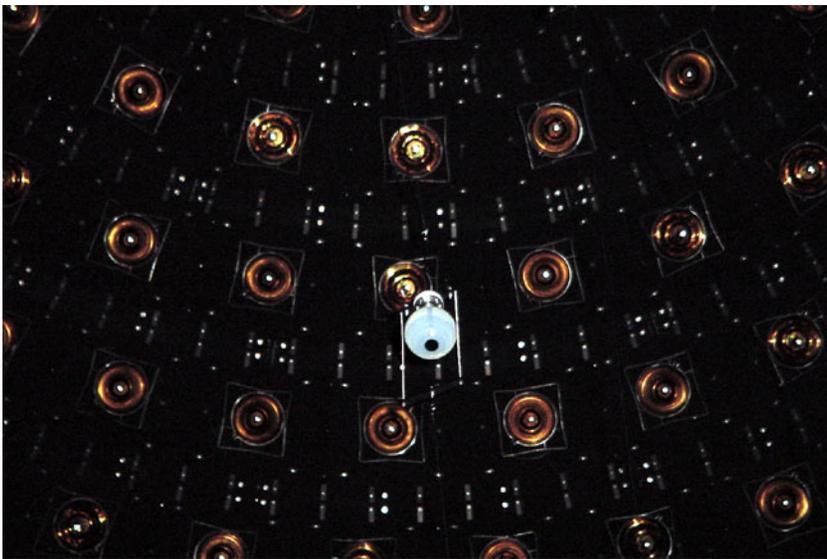


REAL DATA!

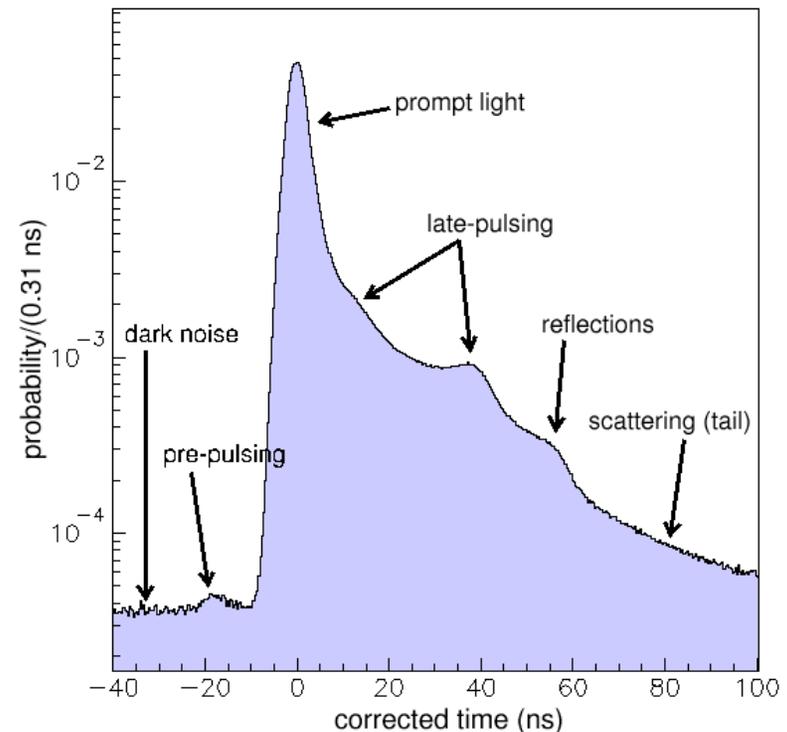
- Nuclear recoil: use scintillation/Cherenkov fraction

Calibration Source 1: Laser

- Four laser flasks are distributed throughout the tank
- Isotropic light with 397/438 nm wavelength, adjustable intensity and known emission point, to study:
 - PMT hit reconstruction: PMT time/charge resolution, pre/afterpulsing
 - oil optical properties: attenuation, surface reflections, scattering



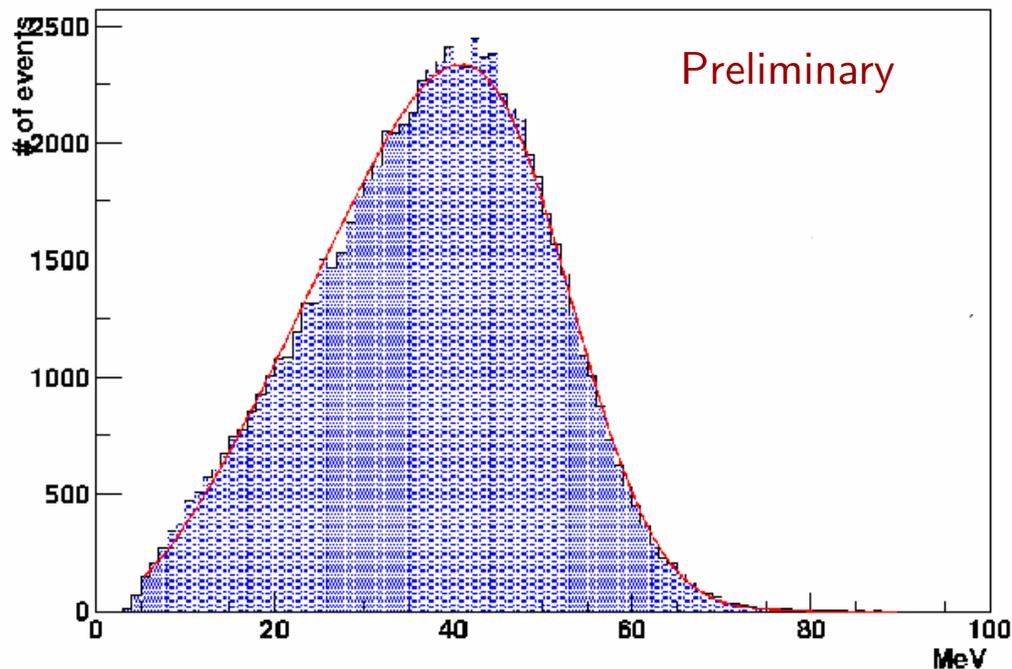
Timing distribution for laser events



Calibration Source 2: Electrons from Cosmic Ray Muon Decays

- “Michel” electrons from muons decaying at rest, where muons are either cosmic rays or beam-induced
- Michel electrons:
 - Look for e correlated in time and space with μ
 - Known energy spectrum between 0 and 52.3 MeV

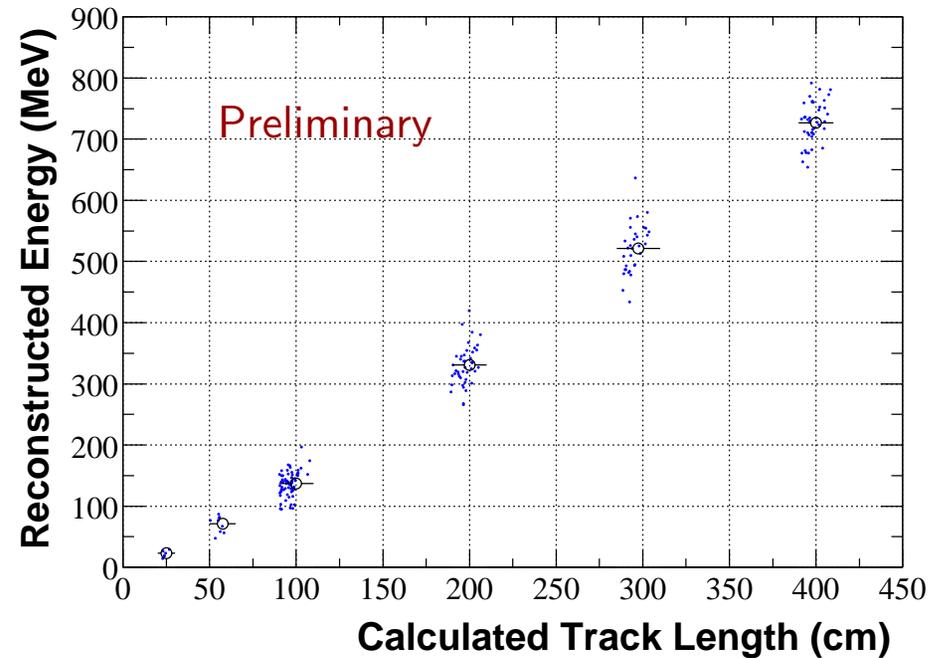
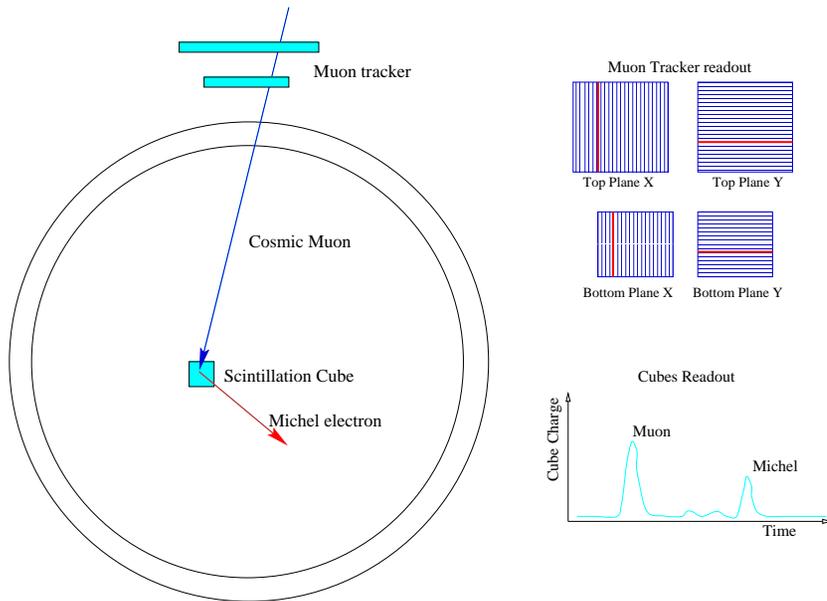
Michel energy spectrum



- Fix energy scale of the detector
- Measure energy reconstruction accuracy: 1% at 52.3 MeV endpoint

Calibration Source 3: Cosmic Ray Muons

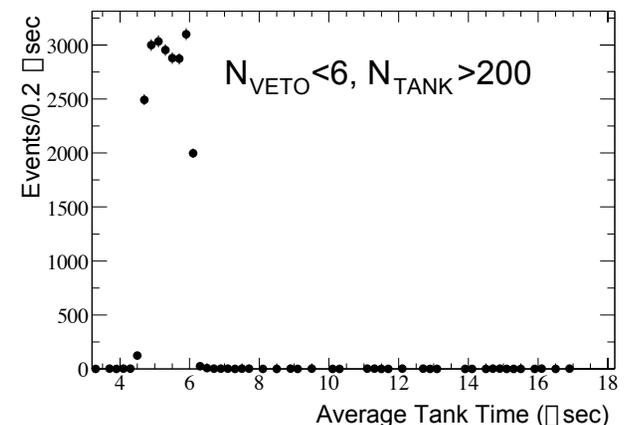
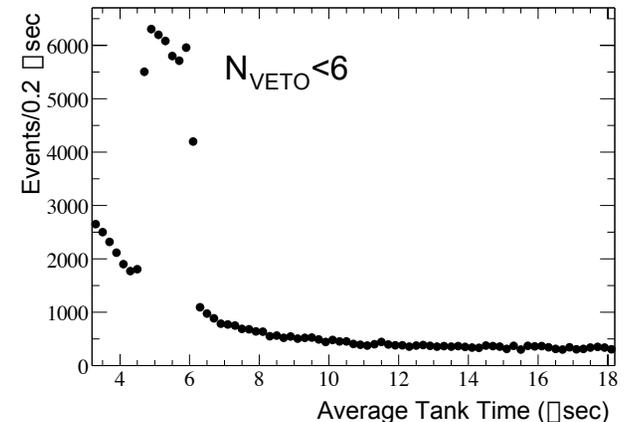
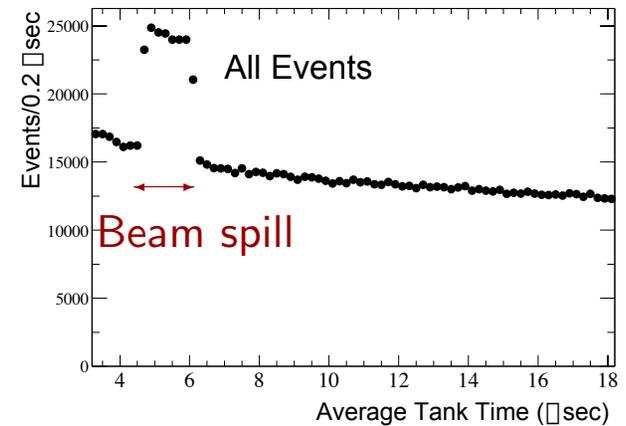
- Muon tracker + cubes system:



- scintillator planes above detector
- seven optically isolated scintillator cubes inside detector
- cross-check on reconstructed track direction, vertex position, energy
- trajectory from muon tracker
- stopping point from cube
- precisely measured pathlength
⇒ independent measurement of muon energy

Neutrino Interactions and Cosmic Ray Backgrounds

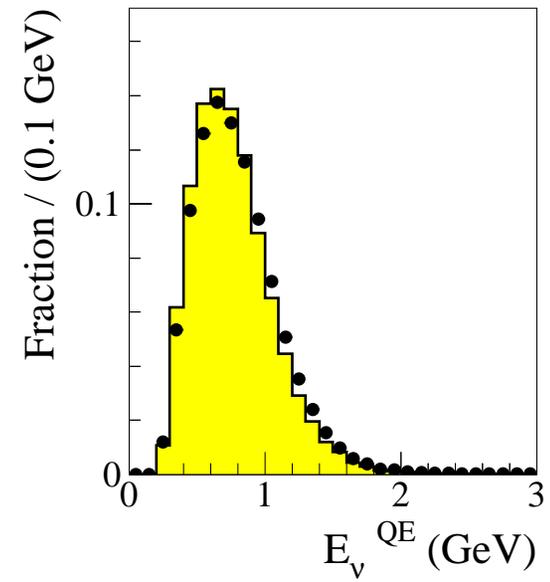
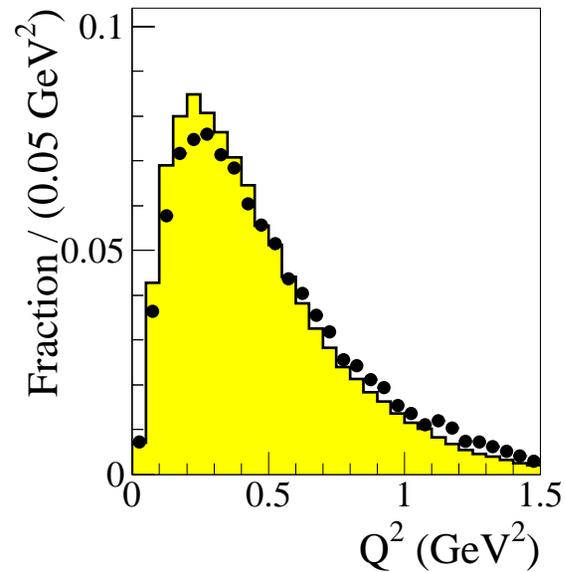
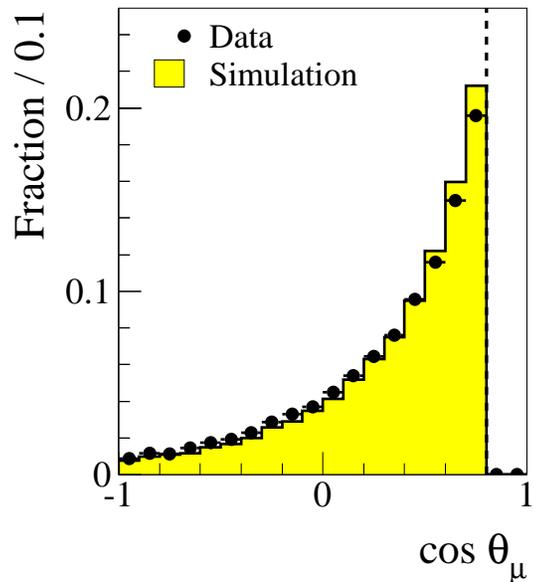
- Data-taking triggered by $1.6\mu s$ beam spill
- PMT hits recorded in $19.2\mu s$ window
- Beam arrives $4.6\mu s$ into window
- Neutrino events seen with no cuts
- Require low veto activity to eliminate cosmic muons
- Require significant light in detector to eliminate cosmic Michel electrons
- $(\text{Neutrino events} / \text{Cosmic ray events}) > 1000$ with simple cuts



Chapter 7

CCQE Distributions for $\cos \theta_\mu < 0.8$

- Compare data and simulations in kinematic region minimizing nuclear effects: $\cos \theta_\mu < 0.8$
- θ_μ : angle between muon and neutrino directions
- $Q^2 = -(p_\nu - p_\mu)^2$
- E_ν^{QE} : neutrino energy



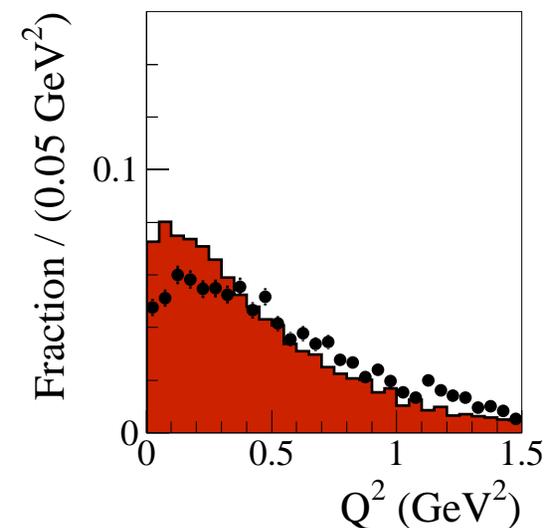
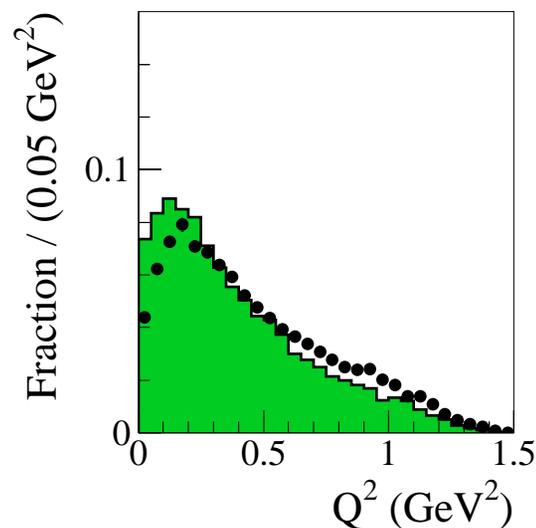
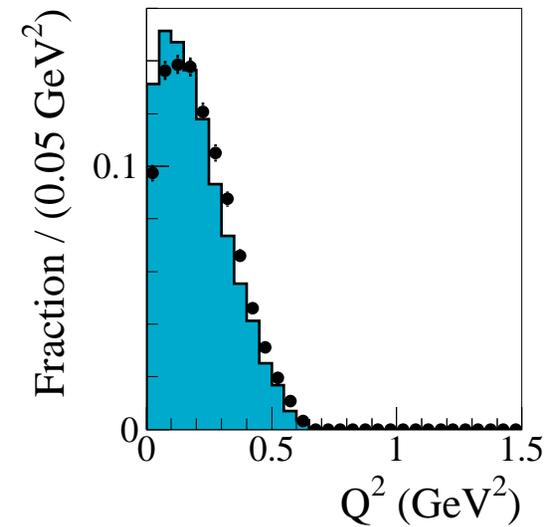
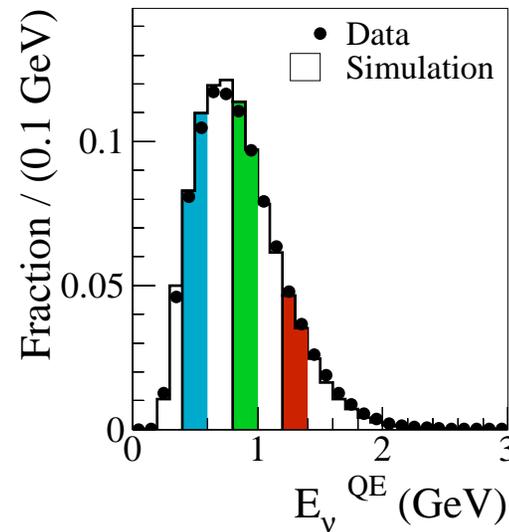
Q^2 Distributions for Separate Neutrino Energy Bins

- Compare observed and predicted Q^2 distributions in separate neutrino energy bins
- Low- Q^2 rate suppression present for all energy bins

- $0.4 \leq E_{\nu}^{\text{QE}} < 0.6$ GeV

- $0.8 \leq E_{\nu}^{\text{QE}} < 1.0$ GeV

- $1.2 \leq E_{\nu}^{\text{QE}} < 1.4$ GeV



Chapter 8

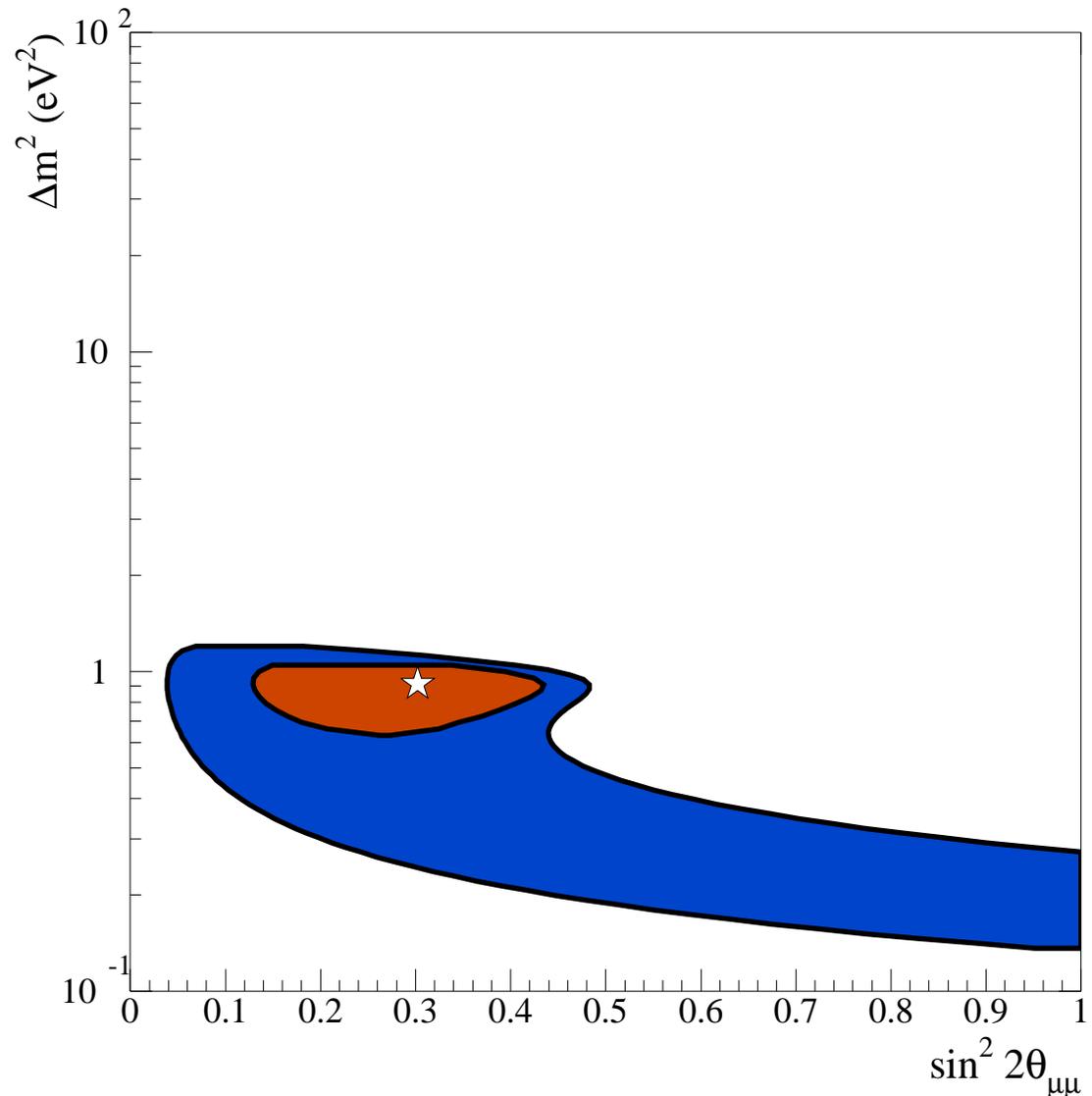
Systematic Uncertainties Affecting the CCQE Rate Normalization

Category	Type	Normalization uncertainty (%)
Flux	π^+ production	10.0
	p-Be inelastic cross-section	3.7
	K^+ production	0.9
	secondaries hadronic model	0.8
	Flux total	10.8
Cross-section	Fermi gas model	10.8
	quasi-elastic axial mass	6.6
	single- π axial mass	3.4
	$\Delta N \rightarrow NN$ rate	1.8
	coherent π production	1.4
	other	1.0
	Cross-section total	13.3
Flux + cross-section total	17.1	

Measurement of Oscillation Parameters via $\nu_\mu \rightarrow \nu_\mu$

- MiniBooNE constraints on oscillation parameters for a simulated oscillation signal allowed in (3+1) sterile neutrino models: $(\sin^2 2\theta_{\mu\mu} = 0.3, \Delta m^2 = 0.92 \text{ eV}^2)$

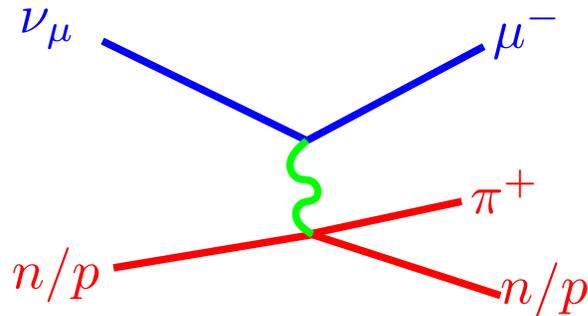
- 68% Confidence Level
(2 dof: $\chi^2 - \chi_{\min}^2 < 2.3$)
- 90% Confidence Level
(2 dof: $\chi^2 - \chi_{\min}^2 < 4.6$)



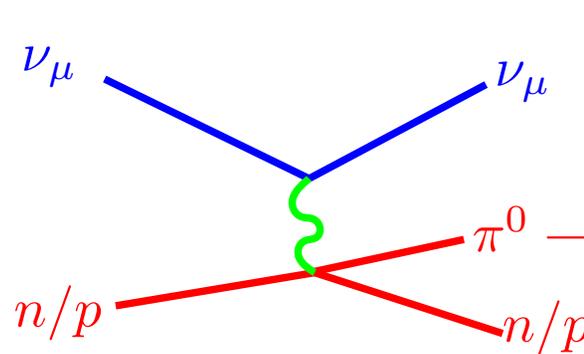
Other MiniBooNE Material

Other Neutrino Interactions Being Analyzed

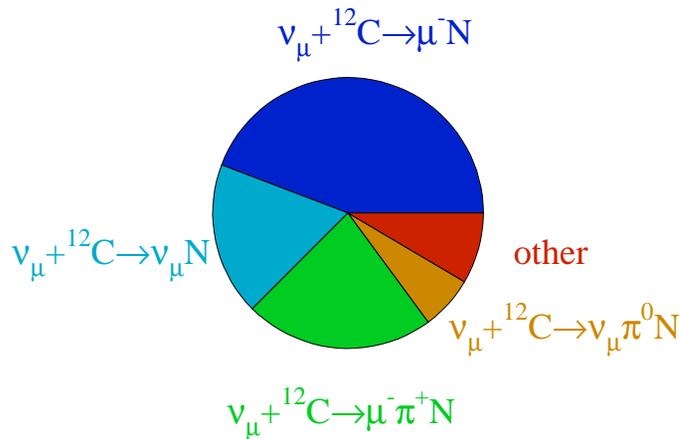
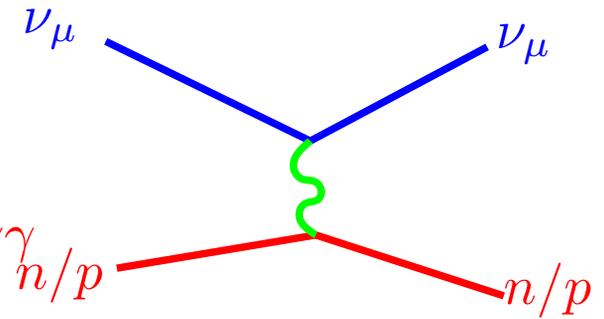
Charged Current π^+ Production



Neutral Current π^0 Production



Neutral Current Elastic Scattering



- Processes at MiniBooNE energies:

Charged current quasi-elastic:	40%
Charged current π^+ :	25%
Neutral current π^0 :	7%
Neutral current elastic:	16%

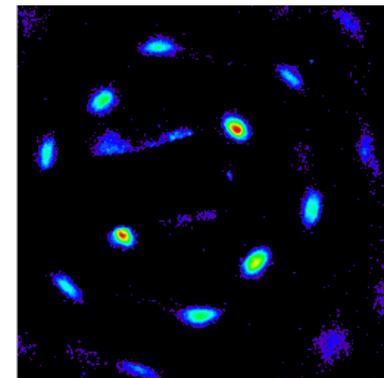
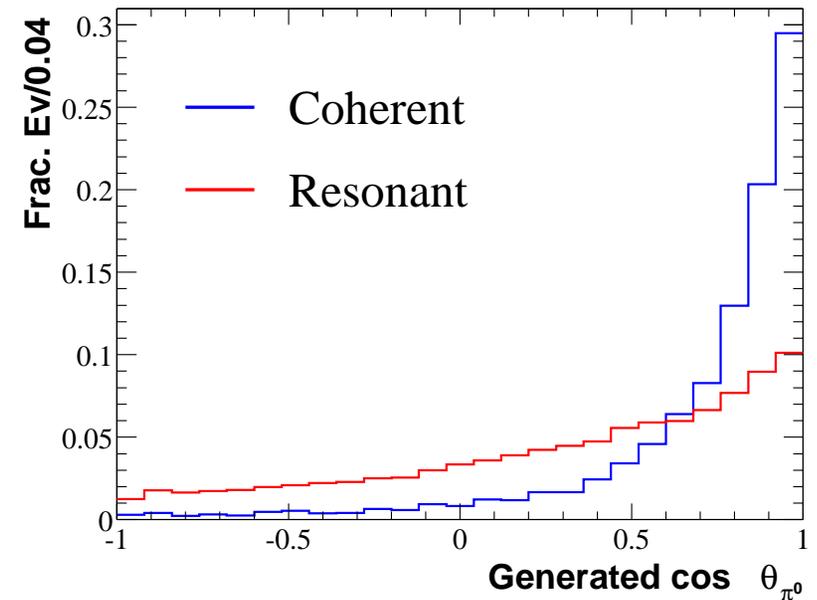
Neutral Current π^0 Production (NC π^0)

• Oscillation physics

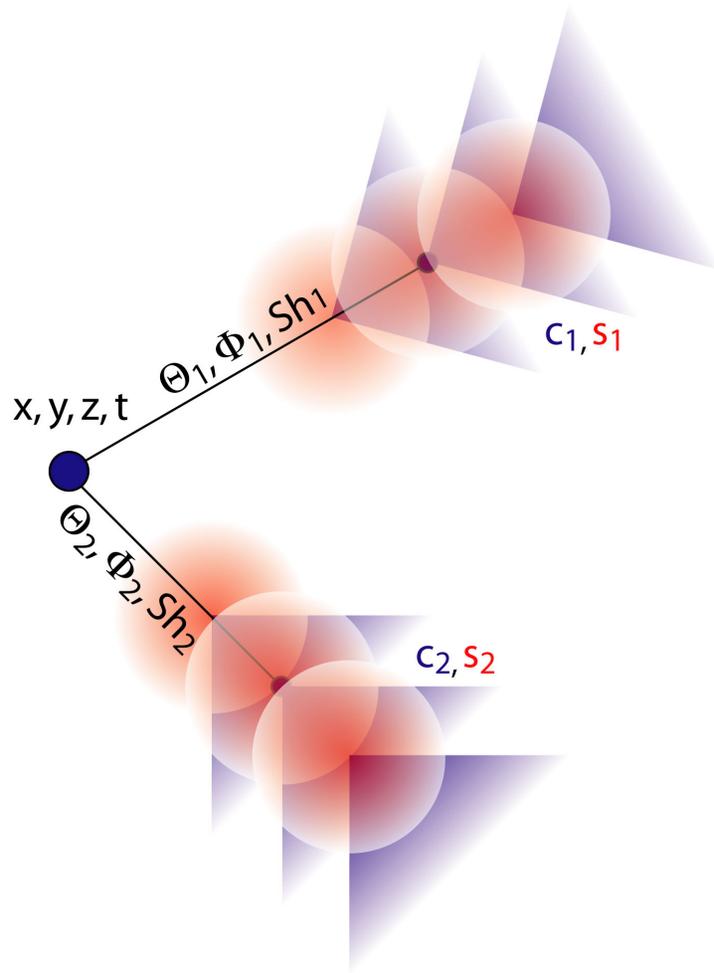
- $\pi^0 \rightarrow \gamma\gamma$ decays are background to $\nu_\mu \rightarrow \nu_e$ searches (not just MiniBooNE!)
- Knowledge of neutral current cross-sections is crucial to distinguish $\nu_\mu \rightarrow \nu_\tau$ from $\nu_\mu \rightarrow \nu_{sterile}$ in atmospheric neutrinos

• Non-oscillation physics

- total cross-section measurement and π^0 angular distribution constrain the mechanisms for NC π^0 production:
- resonant: $\nu + (p/n) \rightarrow \nu + \Delta \hookrightarrow (p/n) + \pi^0$
- coherent: $\nu + C \rightarrow \nu + C + \pi^0$
(similar to Bragg scattering of light)



NC π^0 : Reconstructing Two Ring Events

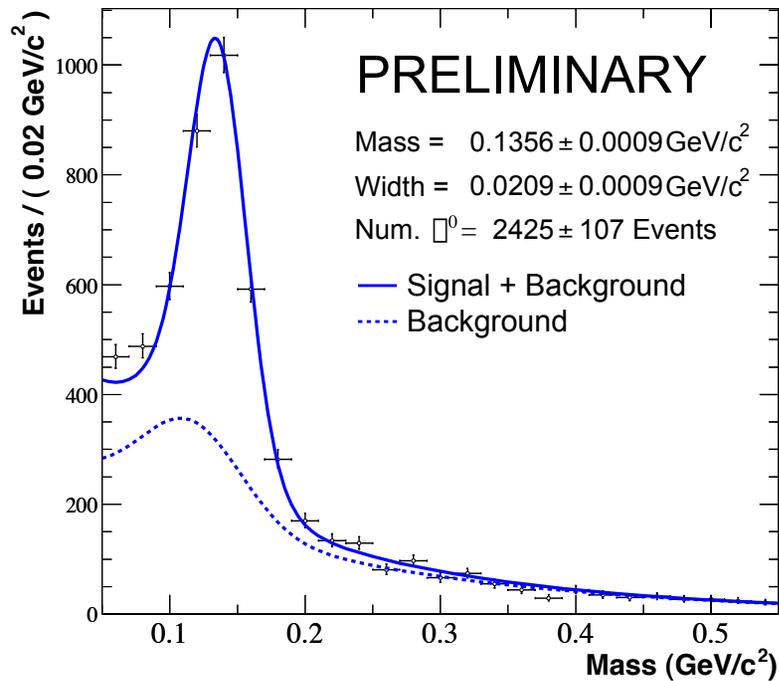


Blue: Cherenkov Light
Red: Scintillation

- $\pi^0 \rightarrow \gamma\gamma$
- γ 's convert and give e -like Č rings
- Fourteen parameter fit:
 - Vertex of decay (4)
 - Direction of photons (4)
 - Mean emission points (2)
 - Č/Sci Intensity(4)
- Kinematics from Č intensity
 - $mc^2 = \sqrt{2E_1E_2(1 - \cos \theta_{12})}$
 - $\vec{p} = E_1\hat{u}_1 + E_2\hat{u}_2$

E_1, E_2 derived from Č rings.
- No (e/μ) ring identification

NC π^0 : Invariant Mass Distribution



- Event Selection:
 - No decay electrons
 - Two \checkmark rings with $E_1, E_2 > 40 \text{ MeV}$
 \Rightarrow signal/background $\simeq 1$
- EML fit to π^0 invariant mass
 \Rightarrow extract yields
- Signal and background shapes are MC-based parametrizations
- Background peak near m_{π^0} expected

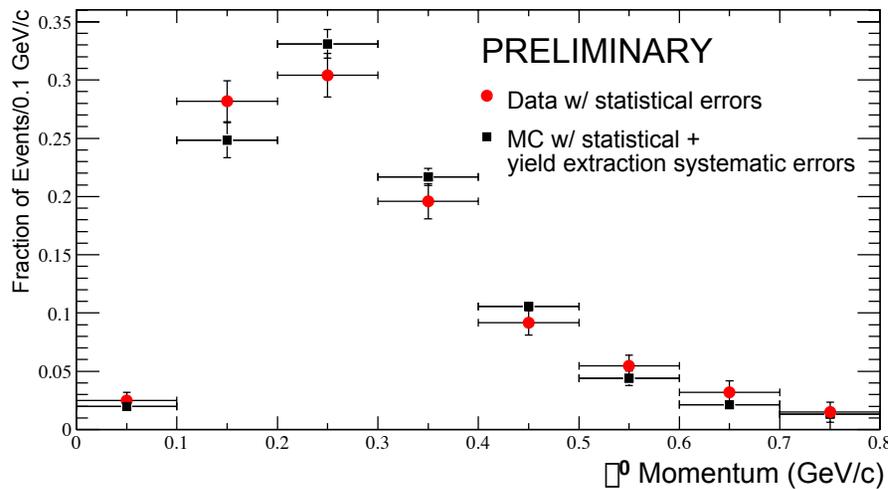
Bin data in kinematic quantities:

- Momentum (p_{π^0})
- Angle relative to beam ($\cos \theta_{\pi^0}$)
- CM decay angle ($\cos \theta_{CM}$)

Extract binned yields

\rightarrow Get distribution

NC π^0 : Kinematics of π^0 Production

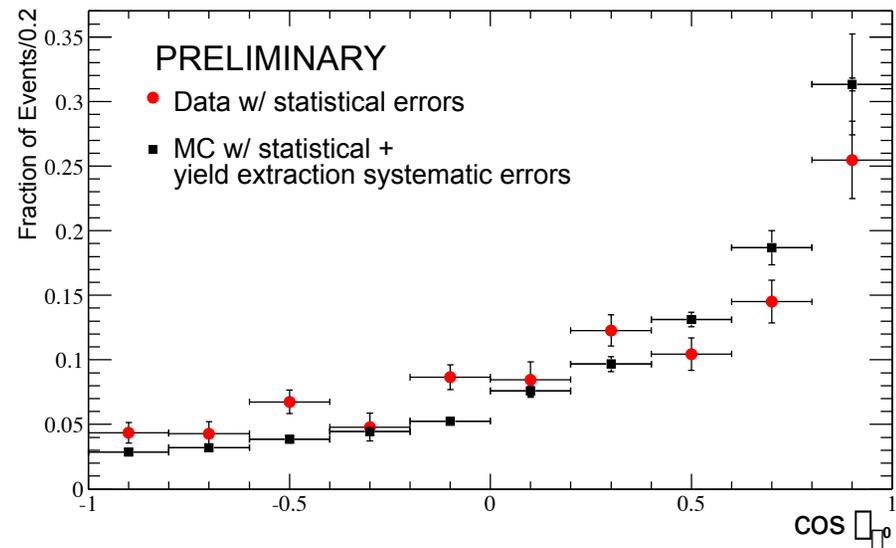


π^0 Momentum

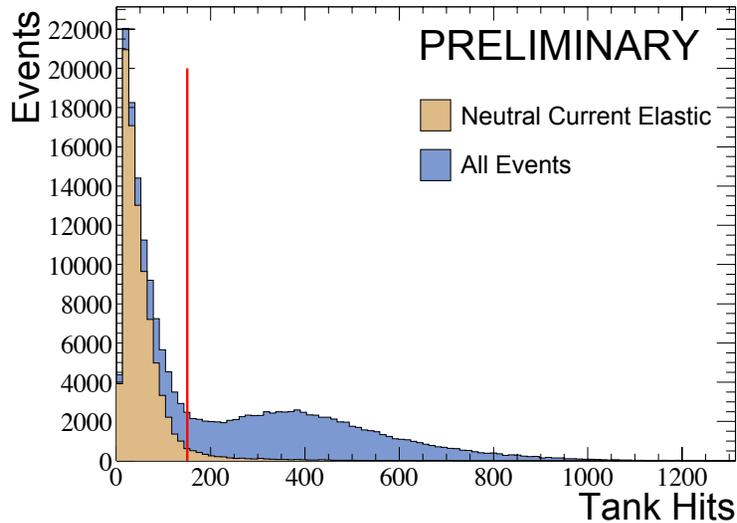
- Good data/MC agreement
- Fall-off at high momentum due to:
 - neutrino flux
 - overlapping \checkmark rings

π^0 Lab Production Angle

- MC assumes Rein-Sehgal cross-sections
- Recent theoretical calculations (e.g. Paschos, hep-ph/0309148) and experiments (K2K) suggest lower contribution from coherent π^0 production
- MiniBooNE will extract coherent contribution



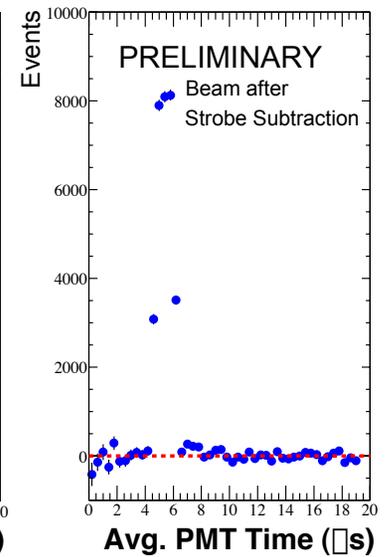
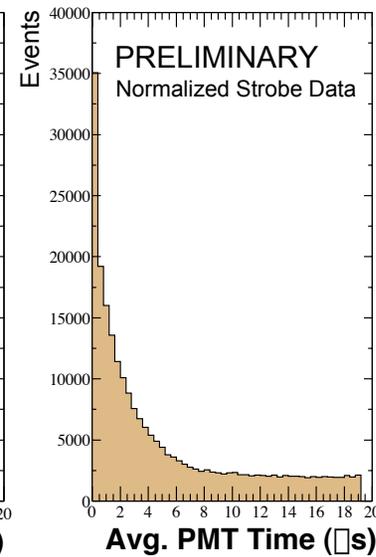
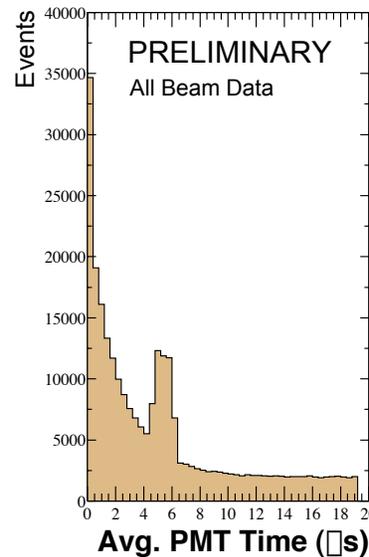
NCE Events in MiniBooNE



- Typically sub- \checkmark :
Dominated by scintillation
- Low hit multiplicity, large scintillation light fraction
- Large cross section ($\simeq 17\%$)

Background subtraction:

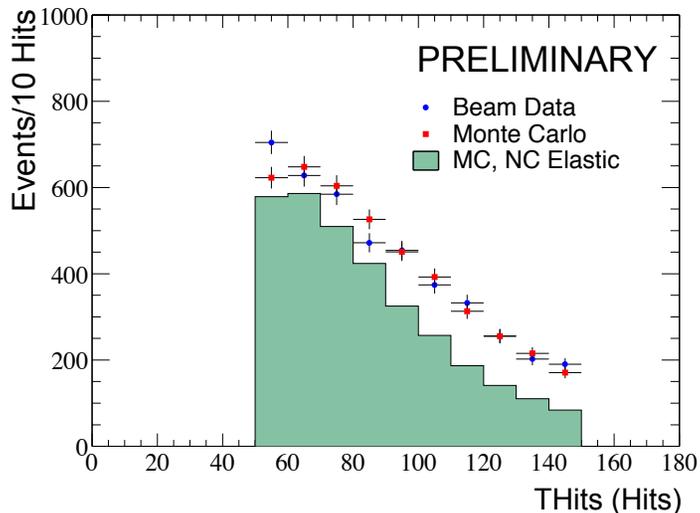
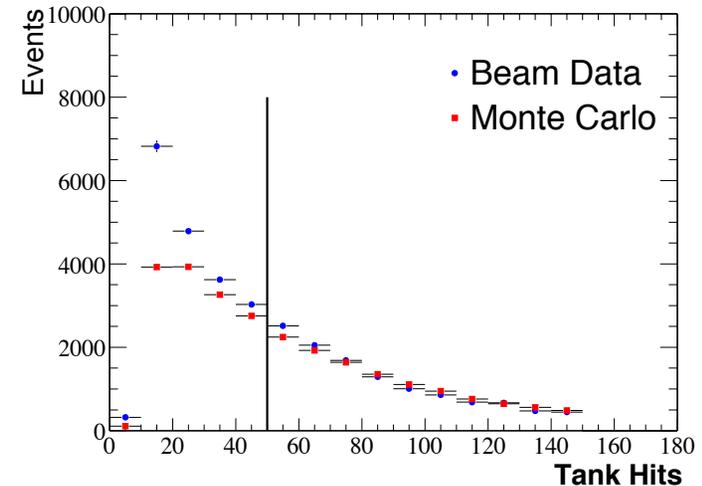
- Beam excess clearly visible also for < 150 hits
- Non-beam background due to:
 - Decay electrons
 - Environmental
- Subtract with random (“strobe”) triggers



NCE: Hit Multiplicity and Scintillation Light

Low multiplicity events:

- Strobe background subtraction
- Unknown component for $N_{TANK} < 30$
- 50 hit threshold for vertex fit
Normalize MC to $N_{TANK} > 50$ yield



Scintillation light selection:

- Fit event vertex for $N_{TANK} > 50$ events
- Calculate fraction of scintillation light
- Select events with scintillation light fraction > 0.5

Agreement for $N_{TANK} > 50$ with/without scintillation light cut.

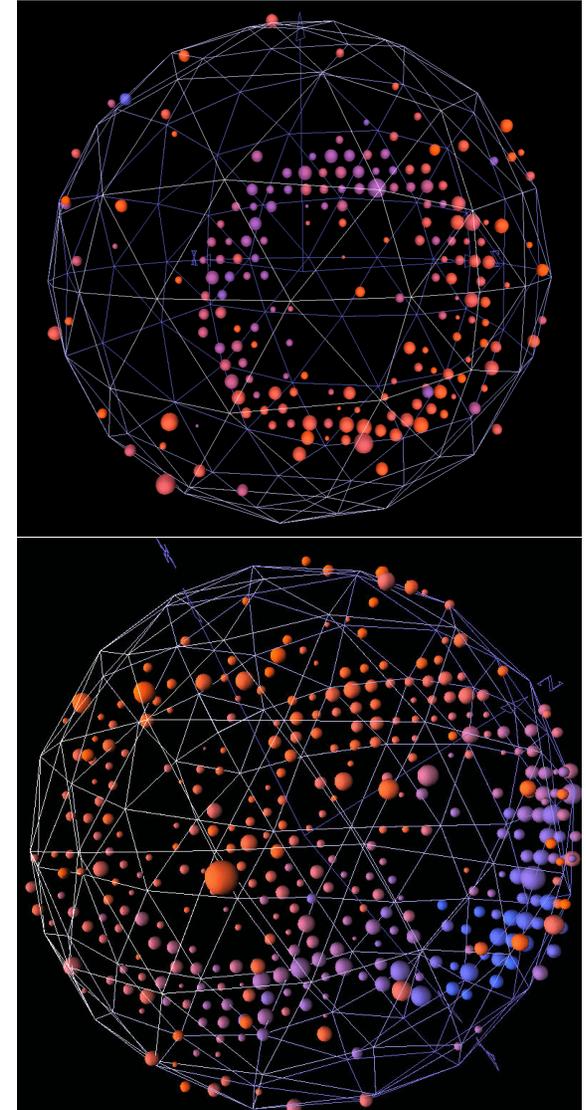
$\nu_\mu \rightarrow \nu_e$ Search

Experimental Signature: $\nu_e + n \rightarrow e^- + p$

- e -like Č ring produced
- p usually below Č threshold

Main backgrounds:

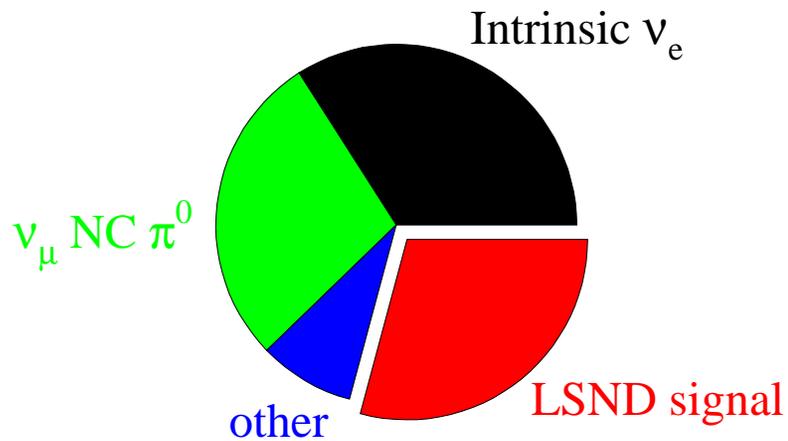
- ν_e CCQE from intrinsic ν_e in beam (K, μ decays)
Produces e -like Č ring
- $\nu_\mu + (n/p) \rightarrow \nu_\mu + \pi^0 + (n/p)$ (NC π^0)
Produces two e -like Č rings
- $\nu_\mu + (n/p) \rightarrow \nu_\mu + \Delta, \Delta \rightarrow (n/p)\gamma$
Produces e -like Č ring



Proposal sensitivity has been updated in November, 2003

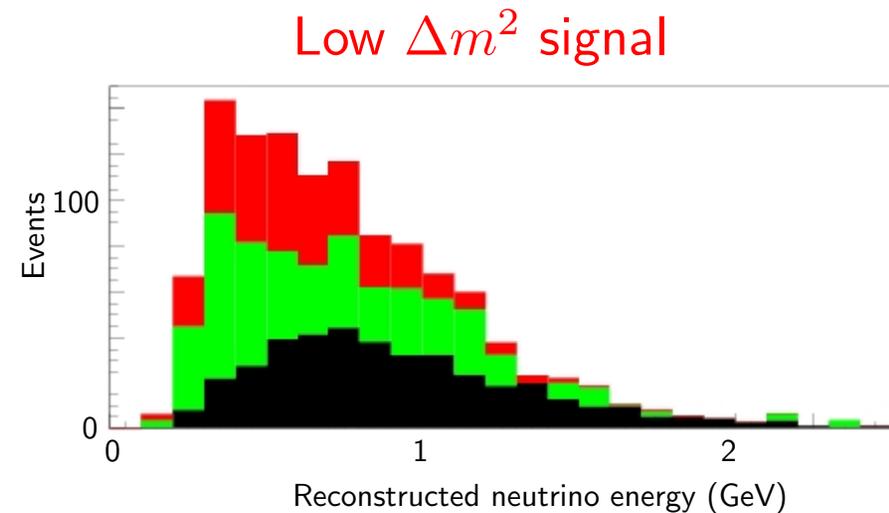
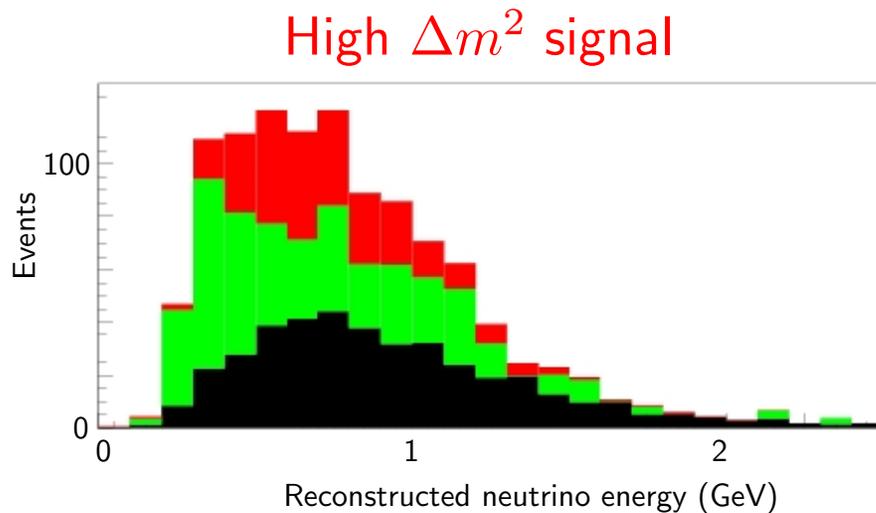
<http://www-boone.fnal.gov/publicpages/runplan.ps>

Signal and Backgrounds



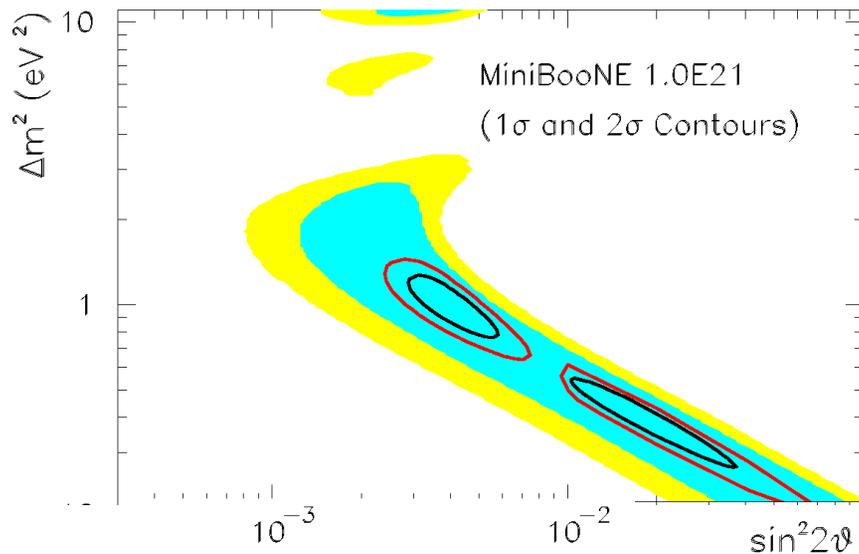
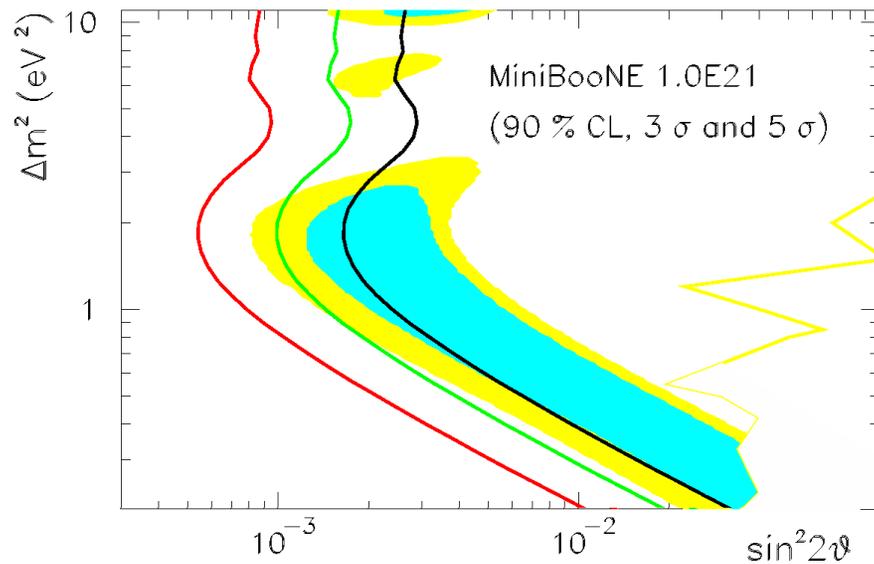
- Expectations for 10^{21} protons on target:
 - $\simeq 300$ signal events (if LSND is correct)
 - $\simeq 700$ background events
- Intrinsic ν_e component in the beam and ν_μ NC π^0 production are main backgrounds

- Signal and backgrounds have different energy distributions:



No Oscillations? Oscillations? Projected MiniBooNE Capability

- Fit energy distribution to extract signal. Estimates based on 10^{21} pot



Null MiniBooNE result:

- 4 σ sensitivity to entire LSND 90% CL allowed region
- Combined analysis of MiniBooNE + LSND would show incompatibility at 99% CL

MiniBooNE confirms LSND:

- Should see $> 5\sigma$ excess at LSND central value
- Distinguish 1 eV^2 from 0.4 eV^2 at 2σ

ν_e CCQE Event Selection

- Fiducial volume cut
- No electrons from μ decays
- Invariant mass assuming two \checkmark rings below m_{π^0}
- Neutrino energy cut to reject high-energy intrinsic ν_e 's
- \checkmark light consistent with single e -like ring
 $\Rightarrow e/\mu, e/\pi^0$ discrimination accomplished via neural networks
- *Nota bene*: LSND oscillation probability is $\simeq 0.3\%$
 \Rightarrow need outstanding $e/\mu, e/\pi^0$ discrimination
- Current estimated event selection performance:
 - μ misidentified as e : 10^{-5} probability (not an issue)
 - π^0 misidentified as e : $3 \cdot 10^{-3}$ probability
 - 20% ν_e CCQE efficiency, relatively flat across relevant energies

Statistical and Systematic Uncertainties

- Measurement is statistics-limited with 10^{21} protons on target
- Systematic uncertainties are non-negligible
- Systematic error assumptions:

Background Source	Uncertainty	Comment
Intrinsic ν_e :		
ν_e from K^+ decay	0.05	HARP uncertainties
ν_e from K^0 decay	0.06	HARP uncertainties
ν_e from μ decay	0.05	Directly tied to ν_μ events
ν_μ Mis-ID:		
NC/Coherent π^0	0.05	Constrained by observed π^0
$\Delta \rightarrow N\gamma$	0.20	Extrapolate from observed π^0
Reconstruction Uncertainties:		
Energy Scale	0.05	Set by Michel e , π^0 , CR calibrations
Efficiency and Selection	0.05	Set by Monte Carlo variation studies